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As Automated Vehicles (AV) continue to advance from research towards deployment, many optimists in the AV industry predict that fully-automated vehicles will be introduced to public roadways by 2025 or even earlier. However, there are variety of open questions and issues that need research, planning, and resolution at State and local transportation agencies to enable successful broad deployment of AV. A key question among these is “what transportation infrastructure improvements or modifications are needed to improve AV performance?”

16. ABSTRACT
A survey was designed and conducted by inviting various AV industry players to practically answer one prime question "what transportation infrastructure improvements or modifications are needed to improve AV performance?" Based on the survey results, selected AV companies were interviewed. The purpose of the interviews was to have in-depth dialog with the AV companies in a private, one-on-one setting on what modifications or improvements they would most desire to improve the performance and reliability of automated vehicles. The topics discussed were ranged from basic infrastructure features such as striping and signage to more advanced topics such as availability of real-time information on road conditions, digital mapping, vehicle-to-roadside communication infrastructure and use of dedicated facilities for AV operations.

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## DISCLAIMER STATEMENT

# Autonomous Vehicles Industry Survey of Transportation Infrastructure Needs

Final Project Report

Contract 65A0735

Prepared by:

California PATH

June 2021

# Contents

# Acronyms

| | |
|---|---|
| AASHTO | American Association of State Highway and Transportation Officials |
| ADASIS | Advanced Driver Assistance Systems Interface Specification |
| ADAS | Advanced Driving Assistance System |
| ADS | Automated Driving System |
| AV | Automated Vehicle |
| CAV | Connected and Automated Vehicle |
| C-ITS | Cooperative Intelligent Transportation Systems |
| DAVI | Data for Automated Vehicle Integration |
| EuroRAP | European Road Assessment Program |
| Euro NCAP | European New Car Assessment Program |
| FHWA | Federal Highway Administration |
| GPS | Global Positioning System |
| HD Map | High Definition Map |
| IESNA | Illuminating Engineering Society of North America |
| IOO | Infrastructure Owner Operator |
| MV | Machine Vision |
| NCHRP | National Cooperative Highway Research Program |
| OEM | Original Equipment Manufacturer |
| SAE | Society of Automotive Engineers |
| USDOT | United States Department of Transportation |
| WZDI | Work Zone Data Initiative |
| WZDx | Work Zone Data Exchange |
| WZED | Work Zone Event Data |
| V2X | Vehicle to X (infrastructure, other vehicles, network, etc.) Communication |

# Executive Summary

Automated vehicle (AV) deployment has the potential to bring about transformational changes to the transportation sector and society as a whole. State and local agencies who own, maintain, and operate the infrastructure have the opportunity to work jointly with the AV industry to provide for safe and efficient operations. A key question being asked by the agencies is: "What transportation infrastructure improvements or modifications do AV manufacturers believe will facilitate and improve AV performance?" Therefore, this project was designed to address this question. The project includes two efforts. One is the literature review. The other is the survey with the AV industry, including an online questionnaire survey and a follow-up interview.

Firstly, we did a comprehensive review of existing research activities that explored the road infrastructure and safety for AVs. In Part I of this report, we provide a summary of the literature review, which includes the following key aspects:

(1) Road infrastructure for AV deployment. Based on the foundations of how AV works, it is clear that a certain level of infrastructure attributes should be maintained in order to achieve a safe deployment of AVs. Well maintained road infrastructure can crucially enhance automated driving systems' performance and availability, therefore contributing to an overall improvement in road safety and traffic efficiency.

(2) Lane markings for AV; Lane marking is probably the most critical factor of roadway infrastructure for human drivers and automated vehicles. Effective lane markings must be visible, both day and night, and in all weather conditions. We provide recommendations for minimum level of performance of lane markings based on three studies from the US and Europe.

(3) Work zone activity information. Work zone information is becoming increasingly important for data-driven agency operations and maintenance. It is also critical information that has an impact on the safe deployment of AVs. In this report, we present the federal initiative and some projects working on standardization, specifications regarding collecting and sharing work zone activity information, which could be leveraged by Caltrans.

(4) Data sharing for AV. There has been increasing emphasis on the importance of data sharing for transportation safety and technological development for connected and automated vehicles (CAVs) from both the public and private sectors. It reinforces the common understanding that access to data is a critical enabler for the safe, efficient, and accessible integration of AVs into the transportation system. Lack of data access could impede AV integration and delay their safe introduction. We provide an update about the Data for AV Integration (DAVI) Initiative launched by the USDOT, which provides high-level guidance regarding AV data sharing.

After the literature review, we implemented the AV industry survey. In Part II of the report, we summarize the survey study, which include the online questionnaire survey and the follow-up interview. The questionnaire started with opening statements, which communicated the purpose of the survey, expected audience, the sponsor, the research team, survey protocol to protect company privacy, as well as steps following the survey. After the opening statements, there were a list of ten questions, which covered both the physical and digital infrastructure, requirement for a minimum performance level, existing infrastructure challenges for AV testing, and suggestions for Caltrans' engagement with the AV industry, et al. Other than the ten questions, we set-up another open-ended question, allowing respondents to provide additional feedback to this topic which were not covered in the questions. At the end of the survey, we also included one question to ask for the survey respondents' willingness to participate in the follow-up interview. The survey was set-up using Google Form. All questions were set as optional. So that respondents have the choice to decide which questions to answer. In other words, it is not mandatory to answer each question. After completing the survey, we analyzed each survey response and used it to draft the interview guide, which was formulated to solicit further responses regarding previous feedback from specific respondents.

In total, 20 companies responded to the online survey. The 20 respondents are from different sectors within the AV industry, including the autonomous car start-up companies, with companies focusing on both passenger vehicles and low-speed shuttle buses; the autonomous truck start-up companies; the autonomous technology provider start-up companies, with companies working on both autonomous driving hardware and software; traditional automotive car manufacturers; and traditional automotive parts manufacturers. The composition indicates that the survey respondents represent the important players in the AV industry well. The responded companies are internationally based, with most of them US companies, some others from either Europe or Asia. In the follow-up interview, 8 out of the 20 survey respondents participated, with 6 of them carried out in the zoom-meeting format, and the remaining 2 provided written feedback.

Combining the results from both the online survey and the follow-up interview, we conclude that:

- The most important roadway characteristics or features that have the potential to benefit the automated driving system (ADS) are (1) digital map and signage; (2) lane markings; (3) work zone and incident information; (4) Vehicle to X (infrastructure, other vehicles, network, etc.) Communication, V2X data; (5) traffic signals; (6) general signage; and (7) lighting.
- Regarding specifications or standards associated with the roadway characteristics, respondents provided some information related to quantifiable specifications for high definition (HD) map, V2X data frequency, and lighting. Other than that, not much information regarding standards or specifications for the roadway characteristics since they are mostly not available yet.
- To the question of "Do you see the need for different infrastructure maintenance requirements when considering the use of ADS rather than human-driven vehicles?" most respondents agreed that the infrastructure would need to be monitored and maintained more stringently if state DOTs want to help improve ADS capability on the roadways. AV companies are interested in obtaining information regarding when road segments are non-compliant with the prevalent or commonly adopted infrastructure standards.
- To the question of "What particular issues (if any) exist for ADS to interpret certain physical infrastructure elements, such as lane marking, traffic signals, HOV/bike lanes, and signs?" the most mentioned physical infrastructure issues were associated with lane markings, signage, traffic signals, and others such as work zones, flashing lights, and retroreflectors.
- Regarding digital features of infrastructure and transportation operations, the following items were the most expected digital infrastructures data to help accelerate ADS deployment, in the order of their selection frequency: (1) work zone and road closure, (2) traffic signal phase and timing, (3) traffic congestion or real-time traffic information, (4) general V2X, and (5) HD maps.
- Regarding preferred channels for receiving V2X data, the majority respondents thought as long as the information is available it can be utilized in various ways. Therefore, it was recommended that the industry should reach an agreement on what V2X technology to use. When it comes to a safety-critical

input to the ADS, it is strongly desirable to have more than one communication path. So V2X plus cellular connection would be good for safety-critical inputs.

- Regarding the support from public agencies, most respondents shared the expectation that the state should consider the V2X policies, such as equipping the traffic signals with V2X information. They recommended having a policy for better maintenance of the infrastructure's physical elements, such as lane markings and road signage, and also a policy for the maintenance of specific operational routes.
- As for the timeline of deployment, all respondents share the notion that AV development is an incremental process. Most of the respondents believe in the mode of shared mobility for public transportation and goods movements in predefined environments. That way, the fleet and service providers will continue to own the vehicles. Regarding ownership of L4 or L5, it will be driven by the acceptance of the L4 or L5 mobility services.
- Most respondents agree that having a venue for engagement between the governmental agencies and the AV industry, and having standards or best-practice guidelines related to infrastructure are very important for AV research and development. The use of consortiums to improve industry engagement is encouraged. There was a consensus that there should be more government and industry collaborations happening where safety is concerned (e.g., sharing data).
- Regarding data sharing, from the AV companies' perspective, the AV testing data is mainly focused on the performance of automated driving systems, but not the roadway features or measurements. There are also various concerns regarding proprietary information embedded in the data, potential liability issues, or the amount of labor work needed for annotating the data before sharing.

This project is an important first step of this mutually beneficial effort to bring together the AV industry and infrastructure owner operators (IOOs). It is highly recommended that the next step should be taken in order to initiate direct and in-depth conversations between the state agencies and critical industrial stakeholders. It is also recommended to begin a concerted research efforts for tools and algorithms that would facilitate relevant key areas of collaborations (e.g., data sharing and data processing).

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# Part I: Literature Review

We did a comprehensive review of existing research activities that explored the road infrastructure and safety for automated vehicles (AVs). The literature included (1) academic research; (2) activities initiated from the federal level in the US, such as FHWA's request for information and NCHRP 20-102 projects; (3) activities of preparing road infrastructure upgrading for AV deployment from three state DOTs (Minnesota, Michigan, and Iowa); and (4) two international initiatives, the report series of "Roads that Cars Can Read" released by EuroRAP and a project conducted by Austroads which identified areas of road infrastructure on key highways and freeways in Australia and New Zealand. The literature review report was initially submitted to Caltrans' in February of 2020, which can be accessed here: https://docs.google.com/document/d/119OoRJuUU4cAoGRYa4Nu1Ocq7h4L8VOQmI56ceEm80c/edit?usp=sharing

After submitting the literature review report, we kept updating the relevant topics covered in the report. In this final report, we will only include the updated literature. As shown in the rest of this Part, the updates include four aspects: (1) the scope of road infrastructure for AV deployment; (2) lane markings for AV, which includes an update of the NCHRP Project 20-102 Task 6 project; (3) initiatives about standardization, specifications regarding collecting and sharing of work zone activity information; and (4) data sharing for AV, which mainly updates the Data for AV Integration (DAVI) Initiative launched by USDOT.

## 1. Road Infrastructure for AV Deployment

Road infrastructure is traditionally seen as a system comprising concrete, asphalt, lane markings, road signs, traffic lights, bridges, and tunnels; in other words, it is an assembly of physical infrastructure. Nowadays, it is complemented by digital infrastructures, such as digital mapping and real-time traffic information. How the road infrastructure, including both the physical and digital infrastructure, will evolve and support AVs' testing and deployment is still unclear. On the one hand, this is due to AV technologies' fast developments. On the other hand, it is also related to the uncertainty in the upgrade of transportation infrastructure. In short, what is achievable at a reasonable cost?

Despite the lack of clear and definite answers, based on the foundations of how AV works, it is quite clear that a certain level of infrastructure attributes should be maintained in order to achieve a safe deployment of AVs. Well maintained road infrastructure can crucially enhance automated driving systems' performance and availability, therefore contributing to an overall improvement in road safety and traffic efficiency. In Europe, the EuroRAP reviewed existing national practices and available research and conducted industry discussions that included representatives from consumer associations, safety organizations, vehicle manufacturers, and sign and marking industries. They found that the combination of inadequate maintenance of roads and differences in national regulations for road markings and traffic signs across Europe was a major obstacle to implementing the Advanced Driver Assistance System (ADAS) technologies, specifically lane departure warning and traffic sign recognition. European Commission even stated that infrastructure deficiencies "…leads to the realization that a true (ubiquitous) SAE Level 5 vehicle may not be possible as comprehensive infrastructure support will likely never cover the entire road network" (*C-ITS Platform Phase 2 Final Report*, 2017)[1]. For human-driven vehicles, driver behavior and inattention are the most significant contributing factors in vehicle crashes. As expected, the human error-related crashes will diminish with the deployment of highly automated vehicles. However, given the

[1] https://ec.europa.eu/transport/sites/transport/files/2017-09-c-its-platform-final-report.pdf

vast range in road quality, infrastructure is likely to play a greater role in traffic safety in the future, while AV failure may also result in additional crashes. It is likely that driver liability will decrease while road authority and manufacturer liability will increase in the era of driving automation (Lawson, 2018)[2].

### NCHRP Project 20-102: Infrastructure Design and Operations

Many research efforts focus on the infrastructure requirement for the testing and deployment of the connected and automated vehicle (CAV). One series of research is the NCHRP Project 20-102[3]. NCHRP Project 20-102 covers a range of CAV initiatives. The objectives of NCHRP Project 20-102 are to (1) identify critical issues associated with connected vehicles and automated vehicles that state and local transportation agencies and AASHTO will face; (2) conduct research to address those issues; and (3) conduct related technology transfer and information exchange activities[4]. As of 2020, 26 individual tasks have been selected/identified by the NCHRP Project 20-102 panel. Combining with some other NCHRP project initiatives, such as NCHRP 14-42[5], there are over a dozen projects that fall in the domain of Infrastructure Design and Operations, as well as IT Infrastructure & Data. Table 1 lists those individual projects, with project number, title, status, and links for project description or reports if it is available. The listed projects are valuable resources for obtaining up-to-date knowledge regarding road infrastructure for CAV, which worth continuously monitoring.

*Table 1. NCHRP 20-102 individual projects, status, link of project description or report*

| **Project No.** | **Project title** | **Status** | **Links of Project Description or Report** |
|---|---|---|---|
| 20-102 (06) | Road Markings for Machine Vision | Completed | http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP20-102-06finalreport.pdf |
| 20-102 (15) | Impacts of Connected and Automated Vehicle Technologies on the Highway Infrastructure | In progress | https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4377 |
| 14-42 | Determining the Impact of Connected and Automated Vehicle Technology on State DOT Maintenance Programs | In progress | https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4571 |
| 20-102 (16) | Preparing Traffic Incident Management (TIM) Responders for CVs and AVs | Anticipated | https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4477 |
| 20-102 (18) | Assessing the Impacts of Automated Driving Systems (ADS) on the Future of Transportation Safety | In progress | https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4573 |
| 20-102 (24) | Infrastructure Modifications to Improve the Operational Domain of Automated Vehicles | Anticipated | https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4680 |
| 20-24 (126) | National Automation Readiness Framework: Coast-to-Coast Automated Mobility | Anticipated | https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4671 |

[2] Lawson, S. (2018). *Roads that Cars Can Read REPORT III: Tackling the Transition to Automated Vehicles*. EuroRAP. https://eurorap.org/new-report-tackles-the-transition-to-automated-vehicles-on-roads-that-cars-can-read/
[3] http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP20-102_CV-AV-Summary.pdf
[4] https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=3824
[5] https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4571

| | | | |
|---|---|---|---|
| 20-102 (25) | Readiness and Effectiveness of Freeway-Based Corridor V2X Applications for Improving Congestion and Safety | Anticipated | https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4867 |
| 20-102 (26) | Dynamic Curbside Management: Keeping Pace with New and Emerging Mobility and Technology in the Public Right of Way | Pending | https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4868 |
| 20-102 (28) | Preparing Transportation Agencies for Connected and Automated Vehicles in Work Zones | Pending | https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4865 |
| 03-127 | Cybersecurity of Traffic Management Systems | Completed | https:\\cyberguidance.transportationops.org |
| 08-116 | Framework for Managing Data from Emerging Transportation Technologies to Support Decision-Making | Completed | http://www.trb.org/Main/Blurbs/180826.aspx |
| 08-119 | Data Integration, Sharing, and Management for Transportation Planning and Traffic Operations | In progress | https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4543 |

# 2. Lane Markings for AV

Lane marking is probably the most critical factor of roadway infrastructure for human drivers and automated vehicles. Effective lane markings must be visible, both day and night, and in all weather conditions. In this section, we first give a background of what is machine vision to automated driving, followed with the definitions of lane markings and the relevant measurements, including retroreflectivity, luminance, and luminance contrast. Then we discuss the influential factors for the effectiveness of lane markings, including physical characteristics (color, width, standard vs. contrast marking), conditions of roadway surface (uniform roadway surface vs. varying roadway surface), and environmental factors (weather, sunlight, wet or not). In the last part of this section, we provide recommendations for minimum level of performance of lane markings based on three studies from the US and Europe.

## 2.1 Machine Vision

For automated driving, machine vision (MV) algorithms have been developed to identify various infrastructure components, including roadway signs, discriminate between different types of lane delineators, and supplement global positioning system (GPS) information in complex environments. Various environmental conditions have been documented as causing MV system problems, including adverse weather conditions, such as fog or rain. As the industry introduces more sophisticated applications with additional or increasing degrees of automated controls, such as lane-keeping/centering, collision avoidance, and overtaking, such automated systems rely on additional information. For lane departure warning, lane position and type are sufficient. For other applications, it also requires lane-curvature knowledge. For example, a collision warning system can generate false alarms when the lane curvature is unavailable or unidentifiable. There is higher complexity of data and information that need to be detected and interpreted by the machine vision systems for highly automated vehicles.

## 2.2 Relevant Definitions

### 2.2.1 Lane markings

Lane markings include two types, longitudinal markings (centerline, lane line, edge line, and lane marker) and transverse markings (shoulder, word, and symbol, stop, yield, crosswalk, speed measurement, and parking space).

### 2.2.2 Retroreflectivity

Retroreflectivity is the portion of incident light from a vehicle's headlights reflected toward the eye of the driver of the vehicle. The retroreflectivity of lane marking is provided by the glass or ceramic beads partially embedded in the surface of lane marking. The most commonly used measure of lane marking retroreflectivity is the coefficient of retroreflected luminance $R_L$, expressed in millicandelas per square meter per lux (mcd/m$^2$/lux.) $R_L$ is an absolute value and is unaffected by night and day.

### 2.2.3 Lane marking luminance

Luminance is the luminous intensity or brightness of any surface in a given direction, per unit of projected area of the surface as viewed from that direction, independent of viewing distance. Lane marking luminance is directly proportional to the amount of the light energy retroreflected by the marking toward a driver's eyes.

### 2.2.4 Lane marking luminance contrast

Luminance contrast is defined as the ratio of the difference between the luminance of a target area and a surrounding background area to the background luminance alone. Luminance contrast is much more important for overall visibility than luminance. Therefore, contrast is more appropriate in measuring a marking's visibility.

$$\text{Lane marking luminance contrast} = \frac{L_m - L_p}{L_p}$$

$L_m$ - Lane marking luminance; $L_p$ – pavement surface luminance.

## 2.3 Influential Factors

The effectiveness of lane markings depends on their luminance (how well the marking stands out on the road) and their retroreflectivity (the amount of light reflected to the driver to make the marking visible). The color of the lane markings also has an impact on the performance. Davies (2017)[6] conducted a static test by placing 2.4 meters long panels of white and yellow lane markings, either 10 or 15 centimeters (~3.9 or ~5.9 inches) wide, in front of a stationary vehicle equipped with a machine vision system. The study found that higher retroreflectivity led to improved detection, but there was an indication that there might be a ceiling for recognition improvements. Color played a role, with yellow being more difficult to detect. Consistently, lines of 15 centimeters wide were detected better than 10 centimeters wide, even if they had lower retroreflecitivity. Conditions of wetness caused a drop in detection quality.

Physical characteristics of the lane marking are the most important factors that would have an impact on the detection confidence by the machine vision systems. As a summary, these characteristics include

[6] Davies, C. (2017). *Effects of Pavement Marking Characteristics on Machine Vision Technology* (No. 17–03724). Article 17–03724. Transportation Research Board 96th Annual Meeting Transportation Research Board. https://trid.trb.org/view/1438482

- Color: white or yellow lane markings
- Width: 4-inch, 6-inch markings
- Standard marking vs. contrast marking (e.g., white 4-inch wide marking paralleled by 2-inch wide black striping on each side)

Conditions of roadway surface have an impact on the detection confidence. For example

- Relatively uniform roadway surface vs.
- Varying roadway surfaces vs.
- Roadways with conflicting messages from previously removed markings, blackout markings, cracking, or rutting;

Environmental factors also have an impact on the detection confidence, such as

- Adverse weather conditions (e.g., fog or rain);
- Glare caused by oncoming vehicle headlamps;
- Sunlight conditions (e.g., sunny vs. cloudy);
- Wet lane marking may have a lower retroreflectivity level in comparison with dry marking;
- Shadows created by overpasses.

## 2.4 Recommendations for Minimum Level Performance

Although more research or studies need to be conducted about the influence of various factors on the performance of lane markings, we summarize the existing research activities, the findings, and recommendations regarding retroreflectivity and contrast ratios of lane marking. The first study is the NCHRP Project 20-102 task 6[7]. The second activity is about EuroRAP Roads that Cars Can Read[8]. The third study is an audit result of freeway and highway in Australia and New Zealand[9].

### 2.4.1 NCHRP Project 20-102 Task 6

NCHRP Project 20-102 Task 6 is about Road Markings for Machine Vision. This project is expected to be useful to the AASHTO/SAE Working Group to develop guidelines and criteria. This project was created to help understand and define how lane markings could be designed and maintained to provide reliable machine vision detection. Data collection for this study was conducted at the Texas A&M University System RELLIS campus, on a closed-course test facility in the winter of 2016 and summer of 2017. A summary of the testing method of this study is provided below.

- Eight scenarios were tested, including (1) daytime dry, (2) nighttime dry, (3) nighttime dry with glare, (4) daytime wet, (5) nighttime wet, (6) nighttime wet with glare, (7) nighttime dry with overhead lighting, and (8) nighttime wet with overhead lighting. The evaluation took place for wet recovery conditions after the markings and pavement were wetted, but not while being wetted.
- Two vehicles, a 2015 Ford Explorer and a 2015 Ford F-150, were used to collect data for this project, at the speed of 40, 50, and 65 miles per hour.
- Both vehicles were equipped with Mobileye 5 series advanced driver assistance systems, as shown in Figure 1. The camera has a horizontal field of view of approximately 40 degrees and a vertical field of

[7] https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4004
[8] http://www.eurorap.org/wp-content/uploads/2015/04/20110629-Roads-That-Cars-Can-Read-June-2011.pdf
[9] https://austroads.com.au/publications/connected-and-automated-vehicles/ap-t348-19

view of roughly 30 degrees. The system utilizes a monochrome camera with a resolution of about 1 megapixel (1280 * 1024).

- The detection confidence rating is an integer value between 0 and 3, with 3 being the highest confidence. The systems require a confidence value of 2 or greater to detect the lane position and lane type for applications such as lane departure warning.
- Handheld retroreflectometers were used to obtain measurements of the coefficient of retroreflected luminance ($R_L$), which is indicative of visibility at night, and the luminance coefficient under diffuse illumination ($Q_d$), which is indicative of visibility during the day.
- Another portable spectrophotometer was used to obtain color (x, y chromaticity coordinates) and luminance (CIE Y) of the markings and pavements.
- The daytime visibility of the markings was characterized with measures of luminance (CIE Y), luminance coefficient under diffuse illumination ($Q_d$), and the MV system geometry luminance ($L_v$).
- The nighttime visibility of the markings was evaluated with measures of the coefficient of retroreflected luminance ($R_L$) and the MV system geometry luminance ($L_v$).

*Figure 1. Mobileye system from exterior and interior of the testing vehicle (Pike et al., 2018[10])*

The premise of this study is that to achieve consistently high detection confidence by the MV system, the contrast ratio of the longitudinal lane markings relative to the pavement needs to be of an adequate level. The lane marking performance characteristics and associated contrast ratios needed for adequate detection by the studied MV system are summarized below.

- Daytime dry testing results indicated that all marking samples with a Y value of 23 or higher had an average confidence rating of 2 or greater. This resulted in a 1.6 contrast ratio.
- Daytime wet testing was inconclusive. There was no correlation between detection confidence rating and the marking Y value—likely due to sun glare during some of the tests.

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[10] Pike, A., Barrette, T., & Carlson, P. (2018). *NCHRP: Evaluation of the effects of pavement marking* [NCHRP 20-102 (06) Final Project Report]. http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP20-102-06finalreport.pdf

- The dry night testing results indicated that marking samples with a retroreflectivity value of 34 mcd/$m^2$/lux or higher (with the exception of one sample observed by the F-150), had an average detection confidence ratings of 2 or greater. This resulted in a 2.5 contrast ratio.
- In wet night conditions, every marking sample with a wet recover retroreflectivity level of 4 mcd/$m^2$/lux or higher had an average detection confidence rating of 2 or greater. This resulted in a 2.1 contrast ratio.
- The results of this study suggest that solid markings are more easily detected by the MV system, although in most instances, the difference is minor.
- During the daytime testing, the MV system detection confidence ratings generally decreased with increased travel speeds (e.g., 40mph vs. 50mph vs. 65mph). The night testing generally showed no impact on speed.
- No clear trend could be identified regarding testing under different levels of cloud coverage. However, the effect of the cloud was not systematically evaluated. Further research would be needed.
- Overhead lighting had adverse effects on the detection confidence of the MV system.
- The contrast lane marking (white 4-inch with black 2-inch on each side) resulted in mixed findings. Results indicate that the black portion of the marking may create glare problems rather than mitigating them. More research about the effect of glare and the ways to reduce the impacts are needed.
- Other factors will influence the markings' detectability that does not deal with the marking characteristics. These factors include the speed of observation, the geometry of observation, glare from the sun, glare from other vehicle lights, vehicle head light quality, street lighting, road surface characteristics, weather conditions, supplemental raised pavement markers, shadows, and other signals on the road surface that could confuse marking detection (removed markings, pavement joints, crack seal, etc.).

### 2.4.2 EuroRAP Roads that Cars Can Read

As a brief introduction of the EuroRAP and the Roads that Cars Can Read initiatives, EuroRAP is a sister program to Euro NCAP. Euro NCAP is the independent crash test program that star rates new cars for crash protection. Similarly, EuroRAP measures roads' safety performance and demonstrates how and where they can be made safer. They examine the relationship between road infrastructure and safety for conventional and automated vehicles (AVs), as AVs become more common in the road network.

Based on an overview of existing national practices and discussions between consumer associations, safety organizations, vehicle manufacturers, and sign and marking industries, EuroRAP and EuroNCAP believe that road markings on Europe's roads should adopt a simple "150 x 150" standard (Lawson, 2018)[11]. More specifically,

- Lane and edge marking should be consistently 150 millimeters wide (which is 5.9 inches).
- These markings in the dry should reflect light at 150 mcd/lux/$m^2$.
- For wet conditions, the minimum performance level should be 35 mcd/lux/$m^2$.

In order to achieve improved performance of road markings, EuroRAP also recommended that

[11] Lawson, S. (2018). *Roads that Cars Can Read REPORT III: Tackling the Transition to Automated Vehicles*. EuroRAP. https://eurorap.org/new-report-tackles-the-transition-to-automated-vehicles-on-roads-that-cars-can-read/

- Use retroreflective markings that are visible under all weather conditions (the simple "150 x 150" standard);
- Harmonize across Europe the color and dimensions of lane markings;
- Install continuous lines to delineate the edge of the carriageway;
- Maintenance of road markings should have budget priority. With all roads properly marked and maintained, they are clearly visible and not confusing.

As recognized by the EuroRAP, the next step needed is an independent survey to find out the extent to which Europe's roads already meet the standard. So the scale of action that needs to be taken to make Europe's roads fit for automated vehicles can be identified. The need for infrastructure Star Ratings for different automation levels can also be explored. For example:

- A road with excellent all-weather lane marking may reduce the run-off-the-road risk to zero. Because there will be few foreseeable conditions under which an AV will not be kept on the road. The high-quality lane marking and the AV's lane-keeping functions may mean that it will contribute to a 4-Star Rating.
- A signalized intersection may be safer and have a higher rating for an AV than a roundabout because it provides more predictable elements of the stop-start maneuver and gives more closely-defined turning maneuvers.

### 2.4.3 Austroads: Road Audit Results in Australia and New Zealand

This project was conducted by Austroads, the apex organization of Australasian road transport and traffic agencies. It is about infrastructure changes to support automated vehicles on rural and metropolitan highways and freeways[12]. It aims to identify current physical and digital road infrastructure areas on key highways and freeways in Australia and New Zealand that automated vehicles using machine vision systems can and cannot interpret. The 2nd module of the project is a road audit, which focuses primarily on the ability of assisted driving and automated driving vehicles to understand infrastructure through camera sensors. More specifically, it focuses on addressing the following key questions: (1) what are the locations, incidence rates, and characteristics of potentially problematic infrastructure; (2) what is the likely impact of each occurrence on real-time CAV operation (e.g., Can a vehicle correctly detect the line or sign on each occurrence? Is real-time driving operation affected because of failure to correctly detect or identify an item?). The audit collected information on the physical infrastructure readiness for machine vision technologies, including longitudinal lane markings, signs, temporary road conditions et al. In this project, Mobileye embedded machine vision cameras were also used to access the real-time performance of the lane markings. Threshold values for measured parameters were used to convert measured attributes into meaningful categories for comparison, as shown in Table 2.

*Table 2. Threshold values for categorizing line markings*

| Attribute | Low | Medium | High |
|---|---|---|---|
| Line width (millimeter) | < 100 | 100 - 150 | > 150 |
| Line width (inch) | < 3.9 | 3.9-5.9 | > 5.9 |
| Contrast ratio | < 2:1 | 2:1–3:1 | > 3:1 |

[12] https://austroads.com.au/publications?f.Subject+Area%7CsubjectArea=Connected+and+automated+vehicles

| | | | |
|---|---|---|---|
| Mobileye detection confidence ratings | 0 , 1 | 2 | 3 |

The following paragraphs summarize the findings and recommendations about longitudinal lane markings from this study. It should be noted that the audit was based on the best case conditions for automated driving and away from intersections and built-up areas. Therefore, AVs' real-world performance is likely to be further diminished in poor lighting, traffic, and weather conditions.

- Of the detected lines, a very large proportion are of an acceptable width
    - The audit results show that all line width categories are either medium (36%) or high (64%).
- The width of the line is likely to be less important than the overall contrast between the line and the pavement.
    - The audit results show that most of the categories are either medium (45%) or low (53%).
- Increasing the use of edge lines will provide a clear benefit for automated driving and human drivers.
    - The presence of left and right lane markings is critical for lane positioning, and there are significant proportions of the road network without edge lines. Increasing the use of edge lines and dividing lines (lane lines and center lines) will provide a clear, immediate benefit for automated driving and human drivers.
- The Mobileye real-time processing results suggest that high contrast lines are three times more likely to be identified and classified correctly as low contrast lines.
    - This may be addressed with line maintenance and materials, wider lines (to improve contrast), and consideration for background luminance (of pavement materials), although in many cases, contrast and retroreflectivity are subject to the current lighting conditions.
- Overall, line quality is an important factor in detecting a line for lane positioning and line width, and consistency seems less important.
- Roadworks and unusual circumstances, obstructions, and variable lighting conditions greatly affect machine vision recognition performance.
    - Where lighting is highly variable, such as alternating between bright sunlight and shadow, vision system performance was reduced.
    - The audit case studies showed that road works, temporary lane closures, and unusual circumstances, in general, caused significant problems for automated driving.

## 2.5 Summary

From the above studies, it is clear that color played a role in detecting lane markings by the machine vision systems, with yellow markings being more difficult to detect compared to white markings. Consistently, lines of 6-inch (~ 15 centimeters) wide were detected better than 4-inch (~ 10 centimeters) wide. It should be noted that the goal of the NCHRP Project 20-102 Task 6 was to identify minimum marking performance levels necessary for satisfactory MV performance so that the focus was on 4-inch wide markings only. According to the Austroads study, the width of the line is likely to be less important than the overall contrast between the line and the pavement.

Regarding the retroreflectivity and contrast ratio, the findings and recommendations from the three studies are somewhat different. In the NCHRP project, for the daytime dry condition, all markings with a Y value (an indication of daytime contrast ratio) of 23 or higher, which resulted in a 1.6 contrast ratio, had an average confidence rating of 2 or greater. For the nighttime dry condition, all markings with a retroreflectivity value of 34 mcd/m$^2$/lux or higher, which results in a 2.5 contrast ratio, had an average detection rating of 2 or greater. For wet testing conditions, the NCHRP project results were not conclusive. The EuroRAP simply adopts the 150 × 150 standard, which means that the lane markings should be a consistent 150 millimeters (~5.9 inches) wide, and these markings should reflect light at 150 mcd/lux/m$^2$ under dry conditions. The Austroads didn't measure the retroreflectivity but only the contrast ratio. The road audit results indicated that markings with contrast ratios higher than 2.0 had detection ratings of 2 or greater.

The somewhat difference in the findings of these studies is mainly due to the variety of methods each study applied. The NCHRP study was conducted in a closed-course testing facility rather than in real-world driving environments to identify minimum performance levels of lane markings. The EuroRAP recommendation was based on reviews of existing national practices and available research, as well as industry discussions that included representatives from consumer associations, safety organizations, vehicle manufacturers, and sign and marking industries. There was no further justification for the values provided by the EuroRAP. The Austroad project was conducted on the real-world roadways on approximately 1,000 kilometers of the road section. The difference in experimental methods largely contributed to the somewhat inconsistent findings among these studies. Therefore, the threshold values or recommended values for retroreflectivity and contrast ratio should be referred for certain conditions (e.g., daytime dry conditions) and with precautions (e.g., whether special conditions of sunlight glare). Additionally, further research with more real-world challenging testing conditions for the machine vision systems (e.g., low-angle sun glare in fall and winter) will be needed.

# 3. Work Zone Activity Information

Work zone information is becoming increasingly important for data-driven agency operations and maintenance. It is also critical information that has an impact on the safe deployment of AVs. In this section, we present the federal initiative and some projects working on standardization, specifications regarding collecting and sharing work zone activity information. It includes FHWA's Work Zone Data initiative[13], the USDOT's Work Zone Data Exchange Project[14], specifically the Work Zone Data Specification.

## 3.1 FHWA's Work Zone Data Initiative

Work zones typically involve many stakeholders to manage and maintain them. Many transportation agencies face the challenge of deciding how to gather and share work zone activity information. Work Zone Event Data (WZED) collection is currently largely ad-hoc and limited in scope to address specific agency needs. Besides, it is not easily shared outside of agency-specific systems. As a result, FHWA's Work Zone Data Initiative (WZDI), launched in 2017, is an effort to enable sharing and application of WZED across the country. WZDI is developing a standard approach for collecting, organizing, and sharing data

[13] https://collaboration.fhwa.dot.gov/wzmp/About%20the%20WZDI/Forms/AllItems.aspx

[14] https://github.com/usdot-jpo-ode/jpo-wzdx/

on the WZED includes the “what,” “where,” and “when” of work zone activities. As a result of this initiative, there will be a structure for organizing the next generation of WZED and data systems to enable local, regional, and national data sharing.

A standardized approach is needed to facilitate sharing critical work zone-related information seamlessly across multiple jurisdictions, regions, and information delivery platforms. Standardized WZED will enable effective coordination of activities and enhanced mobility and safety in and around work zones. It meets specifications for content, structure, and format that ensure data are accurately interpreted when communicated to other jurisdictions and stakeholders.

It is a critical step to advance the work zone management for the deployment of connected and automated vehicles. Specifically, the standardization of WZED supports and enables analysis of likely impacts and resulting enhancements of work zones on traffic safety and mobility, as well as sharing work zone information with connected and automated vehicles. The WZDI consists of a series of products to aid agencies with their work zone event data management practices. The products include:

- Work zone data system framework provides a conceptual architecture for work zone data systems for collecting, storing, disseminating, managing, maintaining, and archiving WZED.
- Work zone data exchange (WZDx) specification creates a basic work zone data specification for voluntary adoption of standard data fed by data producers and data users.
- Work zone event data dictionary provides a comprehensive list of work zone data elements for consideration and serves as a backlog of data elements to add to the WZDx specification over time.

## 3.2 Work Zone Data Exchange Project

Work Zone Data Exchange (WZDx) project is part of USDOT’s Data for Automated Vehicle Integration (DAVI) initiative[15]. WZDx project is a multi-agency collaborative effort focusing on making travel safer and more efficient through ubiquitous access to work zone event data. The current efforts of this project are focused on the voluntary adoption of a basic work zone data specification, which enables Infrastructure Owner Operator (IOOs) to make harmonized work zone data available for third party use. For the longer term, the project aims to get data on work zones into vehicles to help automated driving systems (ADS) and human drivers navigate more safely and efficiently.

Version 1.1 (v1.1) of the WZDx specification is available[16]. The purpose of this specification was to describe a set of "common core" data concepts, their meaning, and their enumeration (as applicable) in order to standardize a data feed specification to be used to publish work zone information. Here "common core" is defined as data elements needed for most work zone data use cases that could possibly be defined, which is summarized in Table 3.

*Table 3. Common core data of the WZDx specification v 1.1*

| Data Name | Data Type | Data Description | Conformance | Notes |
|---|---|---|---|---|
| **identifier** | Data element | A unique identifier issued by the data feed provider to identify the work zone project or activity | Required | Request that this be a standardized identifier for a future version |

[15] https://www.transportation.gov/av/data

[16] https://www.transportation.gov/av/data/wzdx-v11-common-core-data-specification-reference-document

| | | | | |
|---|---|---|---|---|
| **subidentifier** | Data element | A unique identifier issued by data feed provider that provides additional references to project or activity | Optional | This identifier may be used in more than one feed as a reference to an agency project number or permit ID |
| **StartDateTime** | Data Frame | The time and date when a work zone starts | Required | |
| **EndDateTime** | Data Frame | The time and date when a work zone ends | Required | |
| **BeginLocation** | Data Frame | The LOCATION when work zone impact begins along a single road in a single direction (see BeginLocation The impact typically begins where the first channeling device (e.g., cone or barrel) is located. | Required | The method used for designating impact should be included in a static Metadata file |
| **EndLocation** | Data Frame | The LOCATION along a single road in a single direction when work zone impact ends and the traffic returns to normal (See EndLocation) | Required | The method used for designating impact should be included in a static Metadata file |
| **wz-Status** | Enum | The status of the work zone | Optional | See Enumerated Type Definitions |
| **totalLanes** | Data element | The total number of lanes associated with the road segment designated by the BeginLocation and EndLocation | Optional | A segment is a part of a roadway in a single direction designated by a start (BeginLocation) and end (EndLocation) |
| **openLanes** | Enum | The laneType that is opened on the road segment designated by the work zone BeginLocation | Optional | |
| closedLanes | Enum | The laneType that is closed due to the work zone on the road segment designated by the Begin Location and EndLocation | Required | More detailed lane impacts / status will be described in Version 2 of the specification |
| **closedShoulders** | Enum | An enumerated type identifying the shoulder lanes that are closed | Optional | To explicitly state that no shoulders are closed, use *none* |
| **workersPresent** | Data element | A flag indicating that there are workers present in the work zone | Optional | |
| **reducedSpdPosted** | Data element | The reduced speed limit posted in the work zone | Optional | |
| **RoadRestrictions** | Enum | One or more roadRestriction flags indicating restrictions apply to the work zone road segment associated with the work zone bounded by the begin/ end locations | Optional | More details may be added to future WZDx versions; these are included as flags rather than detailed restrictions |
| **description** | Data element | Short free text description of work zone | Optional | This will be populated with formal phrases in a later WZDx version |

## 3.3 Summary

In order to support the testing and deployment of automated driving systems, the work zone activity information is a critical aspect that mostly relies on IOOs to provide. Providing the work zone event data will facilitate the AV's recognition and planning, therefore smooth operation, and help protect the safety of work zone workers. With accurate information about the work zone event, it will help both human drivers and automated vehicles avoid intrusion to the work zone, hence enhancing work zone safety. On top of that, the significance of sharing the work zone event data is directly related to the accuracy of information provided. The core information elements of the work zone activity are the location and time, which can be significantly improved through connected devices.

For the WZDx project, several state DOTs (e.g., Iowa DOT, Michigan DOT, Colorado DOT) and some industrial partners (e.g., HERE, Waze, Toyota, Uber, et al.) have been actively involved in the development of the standardized data specification. The FHWA and USDOT's Intelligent Transportation System Joint Program Office (ITS JPO) are co-leading this project. USDOT has announced plans to fund Work Zone Data Exchange (WZDx) Demonstration Grants, which plans to provide one-time funding for public roadway operators to make unified work zone data feeds available for use by third parties and collaborate on the WZDx specification. Moving forward, there will be more state agencies across the country to pilot the use and share standardized work zone event data using the WZDx specification.

# 4. Data Sharing for AV Deployment

## 4.1 Importance of Data Sharing for AV Deployment

There has been increasing emphasis on the importance of data sharing for transportation safety and technological development for CAVs from both the public and private sectors. Several recently released federal funding opportunities were either partially or entirely looking for data sharing innovations or data analysis tools. One example is the "ADS Demonstration Grants Program", which has one specific goal of providing data for safety analysis and rulemaking. More explicitly, it is to ensure significant gathering and sharing of project data with USDOT in near real-time. Another example is the "State and Local Government Data Analysis Tools for Roadway Safety" program, which focused on building the capacity of the state, local, and tribal governments to use innovative data tools and information to improve roadway safety. It indicates the common understanding that access to data is a critical enabler for the safe, efficient, and accessible integration of AVs into the transportation system. Lack of data access could impede AV integration and delay their safe introduction. Accordingly, USDOT launched the Data for AV Integration (DAVI) Initiative[17], which provides high-level guidance regarding AV data sharing.

## 4.2 USDOT's DAVI Initiative

The purpose of DAVI is to identify, prioritize, monitor, and address data exchange needs for AV integration, as illustrated in Figure 2[18].

[17] https://www.transportation.gov/av/data#:~:text=Overview,across%20the%20modes%20of%20transportation

[18] https://www.transportation.gov/av/data

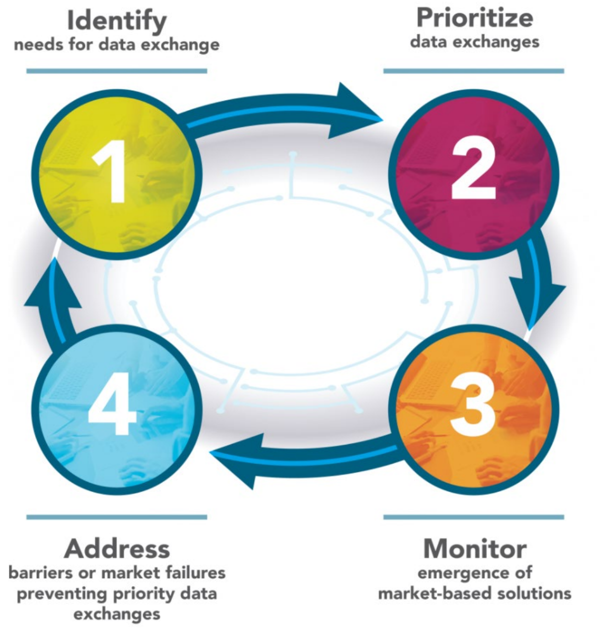



*Figure 2. Four pillars of USDOT's DAVI (source: USDOT website)*

### Guiding Principles

The DAVI guiding principles define an approach to prioritize and facilitate the iterative development of voluntary data exchanges. These guiding principles should be applied to state DOTs when developing any data exchanges with industrial companies.

1. The first principle is to promote proactive, data-driven safety, cybersecurity, and privacy-protection practice.
   1.1. It aims to accelerate the safe integration of AV by encouraging private sector innovation while ensuring appropriate safeguards for cybersecurity, confidential business information, and privacy. Many AV companies share the above-mentioned concerns. Therefore, proactive safety practices should be identified in advance.
2. The second principle is to act as a facilitator to inspire and enable voluntary data exchanges.
   1.2. Industrial partners and government share the objective of bringing safer AVs to market more quickly and recognize the enabling role of data exchanges. U.S. DOT is uniquely positioned to convene stakeholders around mutually beneficial use cases and common standards. U.S. DOT more often will enable others to exchange data via a range of mechanisms.
3. The third principle is to start small to demonstrate value and scale what works toward a bigger vision.
   1.3. It is not practical to define all data exchange opportunities upfront and build policies and capabilities iteratively through collaborative methods.
4. Last but not least, the fourth principle is to coordinate across modes to reduce costs, reduce industry burden, and accelerate action.
   1.4. It was noted that some agencies make duplicative requests for industry information, increasing the cost of partnering with the government. Consolidating and streamlining those requests can reduce costs and increase interest in collaboration.

## 4.3 Summary

The DAVI initiative promotes data sharing to identify infrastructure deficiency (e.g., faded lane marking) and improve roadway infrastructures. For example, as one of the awarded project by the "State and Local Government Data Analysis Tools for Roadway Safety Funding", North Carolina Department of Transportation proposed to develop an AI tool for automated analysis of existing video data that would extract roadside hazards – such as trees, embankments, and steep slopes – on all rural roads in the state, to help identify roadway segments in need of infrastructure safety improvements. Similar research efforts to investigate the data analysis process, tools, or algorithms are necessary for each state on a bigger scale regarding different aspects of roadway infrastructures in their states. However, there are indeed challenges associated with this kind of effort.

# Part II: AV Industry Survey

Automated vehicle (AV) deployment has the potential to bring about transformational changes to the transportation sector and society as a whole. State and local agencies who own, maintain, and operate the infrastructure have the opportunity to work jointly with the AV industry to provide for safe and efficient operations. A key question being asked by the agencies is: "What transportation infrastructure improvements or modifications do AV manufacturers believe will facilitate and improve AV performance?" Therefore, this study is designed to address this question, which includes two parts of efforts. One is the online survey, which was self-administered by the study participants. The other one is the follow-up interview. The interviews were led by the PATH researchers and conducted through zoom meetings. In this section, we firstly summarize the methodology of the study, including development of the questionnaire, implementation of the online survey, and administration of the follow-up interview. Then we present the results and findings from both the survey and interview for each of the survey question.

## 1. Methodology

### 1.1 Development of the Questionnaire

We drafted the questionnaire for the survey, based on the literature review and, in particular, the FHWA's request for information issued in January 2018[19], which was intended to seek comments on planning, development, maintenance, and operations of the roadway infrastructure necessary for supporting ADS. Firstly, the PATH team drafted the opening of the questionnaire in order to encourage the industry's response. The opening statements communicated the purpose of the survey, expected audience, the sponsor, the research team, survey protocol to protect company privacy, as well as steps following the survey. Secondly, the PATH team proposed a list of ten questions be included in the questionnaire, which covered both the physical and digital infrastructure, requirement for a minimum performance level, existing infrastructure challenges for AV testing, and suggestions for Caltrans' engagement with the AV industry, et al. Other than the ten questions, we set-up another open-ended question, allowing respondents to provide additional feedback to this topic which were not covered in the questions. At the end of the survey, we also included one question to ask for the survey respondents' willingness to participate in the follow-up interview. The opening statements and the proposed list of questions were shared with the stakeholders (Caltrans and CalSTA) for further comments. All feedback from the internal stakeholders and the agencies was used to revise the questionnaire further. Then, the PATH team updated the questionnaire, including the opening statement and the list of questions, and sent it to stakeholders for final review. Subsequently, in May 2020, the PATH team received the final approved survey questionnaire from Caltrans.

The cover page of the questionnaire is in Appendix A: Questionnaire Cover Page. The final questions of the survey are included in Appendix B: Survey Questions.

### 1.2 Implementation of the Online Survey

We drafted the study protocol and submitted it for review by UC Berkeley's Committee for Protection of Human Subjects (CPHS). After CPHS review and corresponding revisions, the study protocol was granted in March 2020. Based on the testing protocol, the responses from all companies will be de-identified

[19] https://www.regulations.gov/document?D=FHWA-2017-0049-0001

before sharing or reporting. The company name won't be mentioned during reporting in order to protect privacy and confidential information.  Each survey response will be stored and analyzed with a sequence number only.

To select a better questionnaire survey platform, the PATH team tested two potential platforms for launching the survey, the Survey Monkey platform, and Google Form. The PATH team setup the survey on these two platforms and sent the survey links to Caltrans. Caltrans team pilot-tested the survey and provided recommendations. Finally, the Caltrans team and PATH team decided to use the Google Form for conducting the survey. In the Google Form, all questions were set as optional. So that respondents have the choice to decide which questions to answer. In other words, it is not mandatory to answer each question.

In May 2020, we received the list of AV testing companies shared by California DMV and then started sending survey invitations to each of the 66 companies on the list. Besides, we also reached out to other industrial contacts whose companies have been working on AV technologies but not on the DMV list. In order to encourage participation, we sent out four rounds of email-invitations to the companies on the DMV list for responding to the survey from May to June of 2020.

## 1.3 Survey Response Rate

Till the end of June 2020, 19 companies from the DMV list have responded to the survey. The response rate is shown in Table 4. Besides, one company from the PATH team's contacts also responded to the survey. In total, we have 20 respondents from the survey.  The majority of the respondents (13, 65%) provided the survey feedback through the Google Form. The rest of the respondents (7, 35%) provided the feedback through emails with answers included in the attached documents, either Microsoft Word or PDF documents.

*Table 4. Survey response rate*

| Response | Counts | Percentage |
|---|---|---:|
| No response | 32 | 48.48% |
| Responded | 19 | 28.79% |
| Declined | 12 | 18.18% |
| Address not found | 3 | 4.55% |
| Total | 66 | 100.00% |

The 20 respondents are from different sectors within the AV industry. The composition is shown in Figure 3. Among them, 6 (30%) respondents are from the autonomous car start-up companies, including companies focusing on both passenger vehicles and low-speed shuttle buses; 3 (15%) respondents are from the autonomous truck start-up companies; another 4 (20%) are from the autonomous technology provider start-up companies, including companies working on both autonomous driving hardware and software. Another 4 (20%) respondents are from traditional automotive car manufacturers. The remaining 3 (15%) respondents are from traditional automotive parts manufacturers. The composition indicates that the survey respondents represent the important players in the AV industry well. The responded companies are internationally based, with most of them US companies, some others from either Europe or Asia.

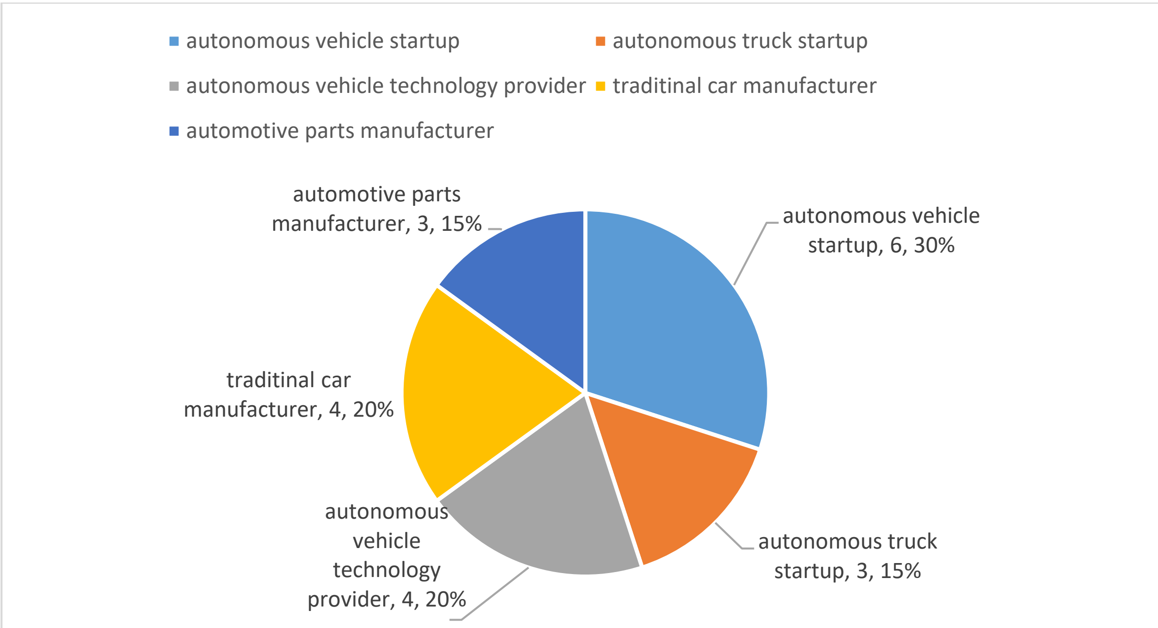



*Figure 3. Composition of the survey respondents (subject to change of the terms)*

## 1.4 Implementation of the Interviews

The purpose of the follow-up interview was to ask respondents to elaborate further on their answers that were unclear or need further information. After completing the survey, we analyzed each survey response and used it to draft the interview guide, which was formulated to solicit further responses regarding previous feedback from specific respondents. For example, the 1st survey question was about the roadway characteristics that would benefit the ADS system. In initial survey feedback, some responses were brief and sometimes lacking in detail. The follow-up interview sought more in-depth answers.  For example, the follow-up question for one company was "*In high-priority, you listed 5.9GHz spectrum for V2I and V2V. In medium-priority, you listed V2X data. Can you elaborate on why you make a distinction?* " We prepared an interview guide for each of the 20 survey respondents.

We also drafted the IRB protocol for follow-up interviews. The protocol was reviewed and approved by UC Berkeley's CPHS in July 2020. After that, we started contacting the survey respondents to schedule follow-up interviews. We used Zoom meeting for the follow-up interviews. The duration of each interview was about one hour. The interview was voice-recorded for transcription and further analysis. Due to scheduling issues or inconvenience, some companies provided written feedback to the follow-up questions instead of an online meeting. The interviews were conducted in August and September of 2020. During the reporting, we de-identified all interview responses by replacing the company names with sequence numbers.

## 1.5 Interview Responses Rate

In total, 8 out of the 20 survey respondents participated in the follow-up interviews, with 6 of them carried out in the zoom-meeting format, and the remaining 2 provided written feedback. The composition of the interview respondents is shown in Figure 5. Among the 8 interview respondents, 2 (25%) are autonomous car start-up companies, including one focusing on passenger vehicles and one focusing on low-speed shuttle buses; 2 (25%) respondents are autonomous truck start-up companies; another 2 (25%) are traditional automotive car manufacturers; 1 (12.5%) is an autonomous vehicle software provider start-up company, and another 1 (12.5%) is an automotive parts manufacturer.

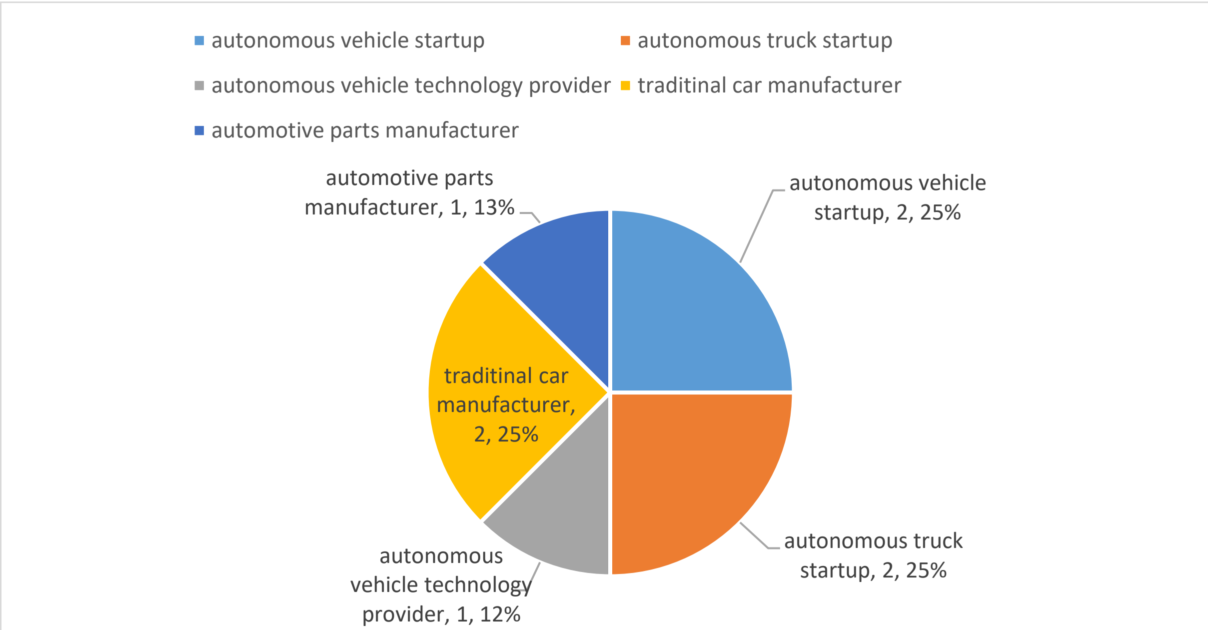



*Figure 4. Composition of interview respondents (same as the previous figure)*

For the interviews conducted through zoom meeting, the voice recording was transcribed using zoom's transcription feature. After each recording is processed, a separate transcript file (.vtt) was generated. The PATH researcher further reviewed the transcript file for each interview to correct the transcription errors. Then the researcher annotated and then analyzed the answers to each interview question.

## 2. Results and Findings

In this section, we summarize the results and findings of each question based on analysis of the respondents' feedback in the online survey and the follow-up interview. In this section, the terms of automated driving system (ADS) and automated vehicle (AV) are used interchangeably.

### 2.1 Question 1

*What roadway characteristics or features do you believe will benefit your ADS systems? You can choose to prioritize them into high, medium and low factors. Examples of roadway features include lane markings, signage, lighting, traffic signals, digital maps and signage, work zone and incident information, V2X data, etc.*

### Survey results

For this question, 18 (90%) companies responded, with 15 of them prioritized their selected items into high, medium, and low factors. Table 5 summarizes the top-chosen roadway characteristics, including digital map and signage, lane markings, V2X, work zone and incidents information, general signage, traffic signals, and lighting. All of the above items were chosen by at least 7 companies. Further elaboration for each roadway characteristics is included in the table. Other roadway characteristics or features were chosen by only 1 or 2 companies. These items include good pavement quality, electronic-signs with high refresh rate, curb location markings, markings for barriers, separation of AV and other road users (to minimize negotiation between them, such as 4-way stop), live traffic, and real-time weather.

*Table 5. Top-chosen roadway characteristics that will benefit the ADS system*

| | Items | Number of responses | Elaborations |
|---|---|---|---|
| 1 | Digital map and signage | 16 | Digital map with road properties (speed limits, road types), with real-time notification of infrastructure changes, well-maintained digital signage. |
| 2 | Lane markings | 14 | Clear lane markings, and lane boundaries |
| 3 | V2X | 14 | V2X information for traffic lights; important traffic signs; work zone and incident information. |
| 4 | Work zone and incidents information | 13 | Work zone uniformity; upcoming work zone in 1/2 mile, and end of work zone; hazards/incident information. |
| 5 | General signage | 11 | Clear/unobstructed, well-lit, consistent/standardized traffic signs; and communication of new kinds of traffic signage with reasonable lead time. |
| 6 | Traffic signals | 7 | Standardized traffic lights |
| 7 | Lighting | 7 | Sufficient ambient illumination. |

Among the respondents, 15 of them prioritized their selected roadway characteristics, which are listed in Table 6. Note that the respondents place different priorities on selected items, therefore the same item may appear multiple times at different levels. At the top of the table, the chosen high-priority items are listed in the order of their selection frequency: digital map and signage, lane markings, work zone and incidents information, V2X, traffic signals, general signage, and lighting. The medium-propriety items include general signage, lighting, digital maps and signage, lane markings, work zone and incidents information. The low-priority items include V2X and others.

*Table 6. Prioritized roadway characteristics*

| ***Priority*** | ***Items*** | ***Frequency*** |
|---|---|---|
| High | Digital map and signage | 9 |
| | Lane markings | 9 |
| | Work zone and incidents information | 9 |
| | V2X | 8 |
| | Traffic signals | 6 |
| | General signage | 3 |

| | | |
|---|---|---|
| | Lighting | 2 |
| | Others (e.g., electronic signs with high refresh rate; curb location markings) | 1 |
| Medium | General signage | 6 |
| | Lighting | 3 |
| | Digital map and signage | 2 |
| | Lane markings | 2 |
| | Work zone and incidents information | 2 |
| | Others (e.g., good pavement quality, live traffic) | 2 |
| Low | V2X | 2 |
| | Others (e.g., digital map and signage, lighting, traffic signals, real-time weather) | 1 |

## Interview results

We asked the interviewees for further explanations of certain roadway characteristics, including cracks in parallel of lane markings, traffic signs, V2X, work zone information, flashing rate of electronic signs, and shared exit. All of these items were mentioned in the survey feedback but not well explained.

- **Cracks in parallel of lane markings:** respondents expect to have limited or no use of bitumen to fix cracks parallel to lane markings over longer distances.
- **Traffic signs**: it is expected that the agencies will communicate new traffic signage with reasonable lead time and provide a nation-wide database with traffic signs and their positions.
- **V2X** is not required to achieve the automated driving task but would be nice for SAE Level 3 to Level 5 automation. It would be helpful to provide the following information:
  - Traffic lights states (current light color and duration)
  - Work zone
  - Incidents
  - Road closures
- **Work zone information:** Communicating the work zone information or just communication of how they display the cones or how they mark the signage can benefit the autonomous vehicles. Similarly, work zone uniformity is not a requirement absolutely needed for deployment. But it is very helpful for the ADS performance and for safety.
- **Flashing rate for electronic signs:** The LED lights on electronic signs flash at a high frequency that human eyes cannot see. The problem for the ADS is that the camera system can see the flashing. Therefore, in order to be identified by the camera system, twice the frame rate of the camera is expected, which is greater than 200 HZ.
- **Shared exit** is problematic to the ADS. The shared exit is the lane that drivers can use either to exit or to going straight. For a human drivers, that's easy to interpret. However, for an ADS, it causes confusions. The system has indecision about whether it is supposed to stay straight or take the exit. Sometimes the ADS goes straight through the middle as it happened many times.

Combining the results from both the survey and interview, we conclude that the most important roadway characteristics that will benefit the ADS are (1) digital map and signage; (2) lane markings; (3) work zone and incident information; (4) V2X; (5) traffic signals; (6) general signage; and (7) lighting.

## 2.2 Question 2

*Are there any specifications or standards associated with the roadway characteristics that you believe would support a minimum performance level? If possible, please provide quantifiable specifications or use specific terms. Some exemplar types of specifications include level of contrast for lane markings, lighting, visibility, markings for barriers, etc.*

### Survey results

In the survey, 13 (65%) companies responded to this question. However, most of the respondents commented on expectations for certain roadway characteristics rather than providing quantifiable specifications. Most of the feedback are about confirmation and further elaboration of the high-priority items mentioned in Question 1 but with more descriptive aspect of each roadway characteristics. These responses are summarized in Table 7. For example, the most mentioned item is lane markings by 7 respondents. The expectations for lane markings are high contrast, non-deteriorated, brighter color for lane markings and a darker color for pavement, well-painted markings with good visibility at nighttime. For work zone information (e.g., road services, blockage, and detour), it is expected to be available either real-time or at least 24-hour ahead of time or pushed by daily emails.

*Table 7. Expectations for certain roadway characteristics*

| ***Roadway characteristics*** | ***Expectations*** |
|---|---|
| Lane markings | • Well-defined and well-maintained lane markings improve vehicle sensor detection of the bounds of operation. Lane markings should be clear and consistent with respect to width, color, and length, and reflective when possible.<br>• New road/lane markings should be protected from erroneous marks (i.e. old/misapplied markings are completely erased).<br>• It is preferable to have fewer parallel road surface markings that are not road/lane-relevant (e.g. concrete expansion joints, tar lines, old markings that have been ground off, etc.). The presence of such markings can make it more challenging to distinguish between real road/lane markings and other markings.<br>• Road markings should also be standardized relative to the location of the roadway. |
| Work zones | • Real-time or advanced digital notification of new construction zones, progress on construction zones, completion of construction zones, or road/lane closures due to special events. This information could be pushed by daily emails.<br>• Scheduled work zone information (e.g., road services, blockage, and detour) should be available 24-hours ahead of time. |
| Traffic signals and traffic control devices | • Traffic signals should have high contrast and be well maintained.<br>• Traffic signals using optical programming and mechanical louvers to limit field-of-view should be limited to make these devices easier to detect by ADS technologies. If strictly necessary, mechanical louvers are preferred to optical programming ones. |

| | |
|---|---|
| | • All steps should be taken to standardize high and low brightness for traffic signal heads, as well as ensure sufficiently large traffic signal head sizing (12-inch diameter is preferred over 8-inch diameter).<br>• Implement standardized and sufficient distance separation of traffic lights that target different classes of vehicles. For example, avoid locating cyclist, bus, and automotive traffic lights so close that confusion between them can be made at a distance.<br>• Traffic light time cards should be available digitally, formatted not as a PDF but in a public database.<br>• Ensure that traffic lights are standardized to be located at the end of an intersection. Some intersections only have lights at the beginning of the intersection and no signal at the far end.<br>• Avoid flashing beacons where a green light can be used. For example, a pedestrian crossing controlled by a HAWK beacon would be much better as a pedestrian-controlled standard green-yellow-red light. Generally, any light for which "off" means "go" can create ambiguities for an ADS due to visual impediments. Both "stop" and "go" directives should be explicit (from the presence of a signal) rather than implicit (from the absence of a signal). |
| Signage | • Signage should have high contrast and be well maintained.<br>• All traffic and speed limit signs should be well maintained.<br>• Signs should be clear of any visual obstruction.<br>• AV operators should receive notice in advance regarding any changes in the placement or content of traffic signs. |
| Marking for barriers | • Reflective marking on barriers will make it easier to detect.<br>• Guardrails and concrete walls provide the ideal barrier, but certain other methods such as large grassy medians and wire rope barriers may also be sufficient. |
| Lighting | • Lighted freeway at night. And no trees next to freeway for less shadow.<br>• Well-lit intersections and roadways will improve camera performance at night. This includes both the use of visible light as well as near-infrared light (800 – 940 nm) for use with cameras that have filters tuned for this spectral region. Near infrared light has the advantage that it will not contribute to light pollution. |
| Standard intersection criteria | • Standard intersection criteria, rules for physical road separation, avoidance of pedestrian on roads. |
| Uniformity Consistency | • There should be uniformity, and not a patchwork of different standards in every state or county.<br>• Consistency across cities on color and application regulations that apply to a section of curb (e.g., in Oakland, white curbs are for 3-minute passenger loading, while in San Francisco are for 5-minute passenger loading. Furthermore, red or black striped curbs indicate time of day bus stops in San Francisco). |

On the other hand, three companies provided information direct or indirectly related to quantifiable specifications for HD map, V2X data frequency, and lighting.

- **For HD map,** respondent #8 mentioned that the accuracy of HD Map < 10cm. Respondent #7 mentioned ADASIS (Advanced Driver Assistance Systems Interface Specification) standard for HD maps (https://adasis.org/). ADASIS has defined an interface to facilitate the distribution of information between the in-vehicle map database, ADAS, and automated driving applications. This enables predictive and vehicle environment data based on HD maps, vehicle position, and other geo-referenced data, improving automated driving performance. In 2020, ADASIS released the new specification v3.1.0 to the public[20]. In the new release, detailed lane modeling and line geometry and additional data (e.g., landmarks) have a resolution of 0.01 meter. In addition, ADASIS members are currently finalizing version v3.2 (Q1/2021), which will include, among other extended lists of traffic signs, localization objects like obstacles and traffic sign face, and a fully defined Application API. Version v3.2 will be ready to be used by autonomous-driving-software developers.
- **For V2X data frequency**, respondent #8 also mentioned that the V2X data frequency should be > 10Hz.
- **For lighting**, respondent #16 mentioned that local lighting conditions should meet or exceed the American National Standard Practice for Roadway Lighting (RP-8) by Illuminating Engineering Society of North America (IESNA).

Besides, 3 companies provided more general comments about standards and specifications for roadway characteristics. For respondent #14, the company has a general expectation of infrastructure improvement, as mentioned "Methods and technologies continue to improve the process of infrastructure management. As such, we expect continued improvement in infrastructure characteristics over time." As mentioned by respondent #7, there are not many specifications and standards for roadway characteristics to allow for a minimum performance level. In addition, these specifications and standards would have to be defined in accordance with the considered level of automation. For instance, dedicated portions of the map could be Level 3 ready, when some others could be Level 2 ready or not ready at all for automated driving due to no map coverage or lack of detectable lane features on the road. This standard information should then be shared in the ADS through an embedded map, for example. To achieve this, clarifications must be made on the expectation for the number and quality of roadway features to enable the minimum performance at each automation level. For respondent #5, the point of view is less dependent on the standards or specification of roadway characteristics, as mentioned "No specific requirements. ADS has to be tested and verified in all kinds of road conditions."

### Interview results

In the interview, we further asked respondent #8 about standard of HD map accuracy during the interview. It turns out that the number was based on their research experiment rather than a standard. It is worth mentioning that 3 respondents emphasized the importance of "uniformity" or "consistency" of those roadway characteristics across different states, counties, or even cities. A human is very good at picking up exceptions, while autonomous system is the other way around. The autonomous system is very good at picking up things which are consistent with what it's been trained, which well explains their general expectation of "consistency is the key".

Overall, not much information regarding standards or specifications for the roadway characteristics are available yet, based on the survey and interview. In the meantime, as mentioned in the literature

[20] https://adasis.org/2020/11/26/new-advanced-driver-assistance-systems-specification-provides-impactful-and-more-accurate-features-to-support-automated-driving/

review section, several on-going projects (e.g., NCHRP 20-102 project) and initiatives (e.g., FHWA's Work Zone Data Initiatives and Work Zone Data Exchange project) are working toward filling in the gaps.

## 2.3 Question 3

*Deterioration is common in infrastructure, and maintenance is performed periodically. Do you see the need for different infrastructure maintenance requirements when considering the use of ADS rather than human-driven vehicles? How might the degradation of roadway features affect your system?*

### Survey results

In the survey, 18 (90%) of the respondents answered this question. As shown in Table 8, among the 18 respondents, 12 (66.7%) mentioned that a different infrastructure maintenance requirement would be needed for ADS compared with human-driven vehicles. In their opinions,

- The need for different infrastructure maintenance requirements when considering the use of ADS rather than human-driven vehicles is obvious. These respondents shared the view that well-maintained infrastructure is important to provide consistently high-automated-vehicle availability and high performance of the ADS. Humans are good at filling in the gaps when markings and signage are missing. Humans can also figure out what other drivers might be doing in difficult circumstances. Considering that a human driver is the equivalent of an SAE level 4 ADS, it should be taken into account that ADS has a limited perception capacity when compared to a human driver.
- Besides, the degradation of roadway features and environmental conditions may affect the automation levels that can be performed by ADS. For instance, a driver assistance system of Level 1 or Level 2 may be highly affected by deteriorated road markings, while a highly automated system at Level 3 automation (Highway Pilot) or Level 4 (Robo-taxi) may be designed and equipped to handle unclear lane markings. Certain roadway features, such as potholes, affect all ADS irrespective of the automation level.

*Table 8. Whether there is a need for different infrastructure maintenance for ADS*

| ***Feedback*** | ***Number of responses*** | ***Reasons*** |
|---|---|---|
| Yes | 12 (66.7%) | "Yes. It needs to more frequent maintenance such as clearing road, painting, and traffic light. If there is any obstacles on the narrow road, the vehicle will be stuck. If there is deep pot hole, it will give big effect to control the vehicle." |
| No | 4 (22.2%) | "There is no such strong demand for infrastructure maintenance, as our target is to develop a more robust ADS with high performance of AI based perception, which reduces the affects from infrastructure." |
| Uncertain: no but also yes | 2 (11.1%) | "There is a lot of research going on to make the ADS system robust to the infrastructure degradations which naturally increases the sensing and computing requirements. However, if this can be maintained, then the sensing and computing requirements onboard the vehicles could be reduced." |

| | | |
|---|---|---|
| Total | 18 (100%) | |

Other than deteriorated or low-contrast lane markings, respondents specifically pointed out other roadway characteristics such as cracks on the road, obscure or poorly placed signage, and poor traffic light illumination. Some respondents further explained the adverse consequences associated with the degradations. A few examples are summarized as follows:

- Deteriorated lane markings could result in the incorrect lane path being followed. Filled up cracks in parallel to lane markings can irritate the detection of the lane width or the lane in general. Lane markings with low contrast towards the road surface are harder to detect and can lead to reduced availability of ADS features that rely on this information. It can also lead to constant steering corrections that make riders feel uncomfortable. Human drivers do have a clear advantage in those situations compared to the state-of-art camera systems.
- Poorly maintained roadway surfaces, such as potholes and buckled asphalt, can increase the risk of damaging vehicle sensors and reduce a vehicle's lifetime durability.
- If there are any obstacles on a narrow road, the vehicle will be stuck. Hence, it would be critical that debris on the road is cleaned up.

On the contrary, the other 4 (22.2%) out of the 18 respondents mentioned that they do not foresee any specific infrastructure maintenance requirements for autonomous vehicle operations. One respondent mentioned that "To achieve the right level of safety for ADS, any infrastructure that is used in the safety process (for human-driven vehicles) should be safe as well. This includes maintaining the infrastructure in working conditions, with monitoring system on the infrastructure itself (such as traffic signals)." Another respondent mentioned that "There is no such strong demand for infrastructure maintenance. Our target is to develop a more robust ADS with a high performance of AI-based perception, which reduces the affects from infrastructure by a lot." Similarly, another respondent also thought that their ADS system doesn't need extra infrastructure maintenance, as their system is primarily a vision-based system that receives information about the driving environment through cameras. Additional environment data that can be delivered to the vehicle will only enhance the performance of the system.

As shown in Table 8, another 2 (11.1%) respondents gave uncertain answers to this question with both no and yes, which implies that more frequent maintenance is nice to have but not essential. For one respondent, their ADS system "can operate when local infrastructure is not perfectly maintained." However, "much like a human driver's experience, the rider experience with their ADS improves as the state of the infrastructure improves." The other respondent has a high expectation of ongoing research, as indicated by this comment: "There is a lot of research going on to make the ADS system robust to these infrastructure degradations which naturally increases the sensing and computing requirements." However, "if the infrastructure can be well maintained, then the sensing and computing requirements onboard the vehicles could be reduced."

### Interview results

Through the interview, most interviewees agreed that the infrastructure would need to be monitored and maintained more stringently if state DOTs want to promote ADS capability on the roadways. AV companies are interested to know or obtain information regarding when road segments are non-compliant with the standards.

One interviewee suggested the following strategy, which could also be applicable to the maintenance of other roadway characteristics. “As a human, I don’t recall any places which have good lane markings. What I recall are areas that have very bad lane markings. This is my suggested rationale about infrastructure for AV deployment. As someone who works in the AV industry, we always look at places where the lane markings are particularly bad. So the key here is to identify areas where lane markings are bad and make them better rather than necessarily trying to make good ones even better.” OEMs need to deliver systems capable of safe operation and handling situations where roadway conditions do not meet minimum operational requirements. But the potential for communication of known conditions by the DOT would assist in determining the ADS system routes and navigating through roadways.

Since many survey respondents mentioned potholes, we further asked about the maintenance need for potholes in the interview. As explained, when the vehicle (any wheel of the vehicle) hits the pothole, the force will be provided to the steering wheel, resulting in a rotating steering wheel. In this case, driving at low speed seems fine. But at high speed, it could have an effect such as lane departure. If there are deep potholes, it will have a big impact on controlling the vehicle. A pothole followed by a flat tire can generate a very dangerous scenario.

An increased rutting issue could potentially emerge as an automated truck holds the lane better than a human. There is no scientific proof for that yet. But thinking this at scale with thousands of automated trucks on the road, it could be an infrastructure issue from a state DOT’s perspective.

In addition to the higher requirement of maintenance for ADS, two respondents also suggested how the roadway maintenance could leverage the widespread of AV deployment. For example, through the widespread deployment of AVs that are constantly monitoring road and infrastructure conditions, there will exist an opportunity to optimize the repair and maintenance of roadways so that areas of real-time observed need by AVs can be addressed first rather than relying on a traditional maintenance schedule. Another respondent suggested a more detailed requirement for infrastructure maintenance. “Firstly, define a clear threshold for the characteristics mentioned above (e.g., bad lane markings, maliciously modified traffic signs); Then, check every 2 years. If it is worse than a threshold, it should be fixed. Vehicle perception can, however, help on identifying critical zones, helping to target the necessary maintenance.”

The combined feedback from all respondents indicates that the majority of companies expect higher requirements of infrastructure maintenance for ADS than the current human-driven vehicles. The rationale is that humans are good at filling in the gaps when infrastructure deteriorates. Humans can also figure out what other drivers might be doing in difficult circumstances. It should be considered that some automation systems have a limited perception capability compared to a human driver. The degradation of roadway features has adverse impacts on ADS' availability and performance. Some respondents either have high confidence with their own ADSs or have high expectations with the on-going research, which they believe will be sufficient to handle the degradation of roadway features. However, they also acknowledge that with the well-maintained infrastructure, the performance of their ADSs could be enhanced.

## 2.4 Question 4

*What particular issues (if any) exist for ADS to interpret certain physical infrastructure elements, such as lane marking, traffic signals, HOV/bike lanes, and signs? Please give specific examples if applicable.*

### Survey results

In the survey, 15 (75%) companies responded to this question. All the physical infrastructure elements mentioned in each response were extracted and then summarized across all responses. As shown in Table 9, the most mentioned issues are associated with lane markings by 8 responses, signage by 6 responses, traffic signals by 5 responses, and others with a sub-total of 5 responses.

*Table 9. Most mentioned issues with physical infrastructure elements*

| ***Physical infrastructure elements*** | ***Frequency*** | ***Details of the issues*** |
|---|---|---|
| Lane markings | 8 | Worn lane marking makes the ADS confuse about where the road center is. |
| | | Lane bleached out lane markings, especially in parallel with crack or fixed cracks in the road can be hard to detect, especially in sunny conditions (I405 and I5 north LA area). |
| | | Yellow lane markings on the concrete road surface and un-unified lane coloring. |
| | | Old lane markings need to be cleared. Old lane markings that coexist with new up-to-date lane marking will confuse the ADS system. |
| Signage | 6 | Branches of trees on the road block many of the traffic signs. |
| | | Traffic signs sometimes cannot be detected in time, they could be blocked by leaves, or it is too dark to be recognized. |
| | | Traffic signs can be hard to interpret, especially when it comes to the association between detected signage and the ego lane. The issue is, “does this sign apply to me?” |
| Traffic signals | 5 | ADS failed to recognize traffic lights placed at poor position or angle. |
| | | Traffic signals can be hard to interpret, especially when it comes to the association between detected traffic signals and the ego lane. |
| | | In particular lighting conditions (e.g., sun position, viewing angle, trees/leaves obstructing the view, location of lighting, LED vs. analog), the ability of the ADS to perceive and recognize traffic lights can be difficult. |
| | | In many cases in the US, it is hard to correctly refer a traffic light hanging above or behind an intersection to its relevant lane. |
| Others (work zone; flashing lights; retroreflector) | 5 | In a predefined environment for a level 4 AV system like ours, issues come when the environment changes (construction work zones, temporary road closures).<br>It is hard for current camera systems to properly detect school zone signage in combination with flashing lights or flashing signs.<br>A retroreflector is a common challenge for LiDAR sensors. |

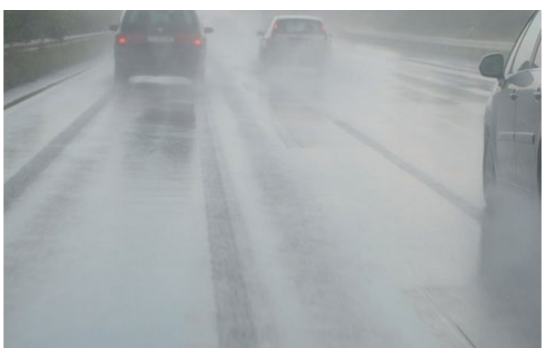
Examples of issues for each physical element are presented in the rightmost column in Table 9.

- For lane markings, the issues include worn-out, cracks and fixed cracks in parallel with lane markings, co-exist with old markings, low contrast, un-unified coloring, which are well-aligned with the expectations of lane markings mentioned for Question 2.
- For signage, mainly three issues were mentioned. One issue is visually obstructed by other objects, such as tree branches or leaves. Another issue is the low contrast of the signage. The 3rd issue is the difficulty to tell the relevance between certain detected signage and ADS' ego-lane, which could be caused by the position or angle of the signage or the roadway structure.
- Similarly, for traffic signals, two main issues were mentioned. One is the perception of traffic lights under certain lighting conditions (e.g., sun position, viewing angle). The same problem under these conditions similarly exist even for human drivers. The other issue is also about the relevance between the detected traffic signals and the ego-lane.
- Other issues were mentioned by a fewer number of respondents, such as work zone and temporary road closure, a combination of school zone signage and flashing lights, and retroreflectors.

## Interview results

Other details of lane boundary issues were further explained by the respondents during the interview.

- As shown in Figure 5(a), rain marks are caused by vehicles driving ahead of the ego vehicle on the wet road surface or by water-filled ruts. Often these rain lines run along the direction of travel. Rain marks can show a similar contrast in the image like real lane-markings in rain and wet surface conditions;
- As shown in Figure 5(b), stationary vehicles were identified as lane boundaries;
- It is hard for the camera system to identify the poles when they are tall and thin, as shown in Figure 6.


a

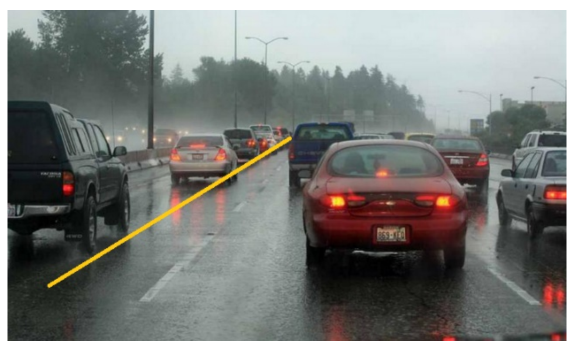

b

*Figure 5. Rain marks and stationary vehicles identified as lane boundaries*

*Figure 6. Tall and thin poles*

Regarding the problematic intersections, some respondents listed detailed issues at intersections, which include:

- No clear lane lines to follow;
- Missing stop lines at stop sign;
- Unclear and not-uniformed pedestrian crossing lines;
- Unclear mapping between traffic signals and lanes.

## 2.5 Question 5

*What types of digital features of infrastructure and transportation operations, if available, do you believe would help accelerate safe and efficient deployment of the ADS? Types of information include traffic signal phase and timing, work zone or road closures, incidents, traffic congestion, etc.*

### Survey results

In the survey, 18 (90%) companies responded to this question. From each response, we extracted the digital features of infrastructure and transportation operations that would help accelerate ADS deployment. Frequency and further explanations for each feature are shown in Table 10:

- Work zone and road closure was mentioned by 12 respondents.
- Traffic signal phase and timing is very helpful when the signals are hard to detect. It was mentioned by 7 respondents.
- Traffic congestion or real-time traffic information was mentioned by 6 respondents, which would help ADS to interpret the environment better and react.
- General V2X, including V2V and V2I, was mentioned by 5 respondents. V2X was believed to accelerate safe and efficient deployment of the ADS, especially in cities.
- HD map is a critical part of making safe ADS, which was mentioned by 5 respondents. HD Map needs to have information about the center of the road, lane marking information, intersection information, and so on.
- Other features such as authority vehicles, obstacles on the road, location for curb pick-up and drop-off, and HOV lane usage and status were also mentioned but less frequently than the other digital features.

*Table 10. Most mentioned digital features that would accelerate ADS deployment*

| ***Digital features*** | ***Frequency*** | ***Explanations*** |
|---|---|---|
| Work zone and road closure | 12 | Work zone and road closures would be considered in the mission planning of the ADS to operate routes. |
| traffic signals phase and timing | 7 | Traffic signal phasing and timing would be helpful if traffic signals are obstructed. As noted above, traffic signal time cards would ideally be provided through a public database rather than via PDF. |
| Traffic congestion | 6 | Prior information on traffic congestion would help ADS to interpret better and react. |
| General V2X | 5 | 5G or DSRC. It will surely accelerate the safe and efficient deployment of the ADS, especially in cities. |
| HD map | 3 | HD Map needs to have information about the center of the road, lane marking information, intersection information, and so on. |

| | | |
|---|---|---|
| Others (authority vehicles; obstacles on the road; location for curb pick-up and drop-off; HOV lane usage and status) | 6 | Proactive sharing of the location (where they are located) and activity (what is the pathway) of certain fleet vehicles that modify other vehicles' behaviors, such as emergency medical services (EMS) and school buses, can also accelerate deployment and reduce risks. Other examples of these vehicles also include authority vehicles and school buses Dedicated location for curb pick-up or drop-off. |

### Interview results

Work zone and road closure information is needed for the automated trucks. Blockage or closure due to road work or accident could mean the automated truck is stuck. It can't do a U-turn, and it can't pass the blocked or closed zone. Therefore it is a major inconvenience factor for the AV as well as the surrounding traffic. Firstly, an agreement is needed on what signage will be used for construction zones or accident zones so that autonomous vehicles have a consistent and distinctive symbol to respond to. Additionally, standardizing the access to this data (digital infrastructure) would be a benefit ADS providers could leverage from the public agencies.

ADS generally relies on accurate detection of lane markings and signage on the road and traffic signals to make decisions of its next actions. In case these physical infrastructure elements are not visible to the sensors (e.g., cameras, LIDAR), ADS may fail to make the right decisions. Maintaining up-to-date digital assets that provide information on roadway structure and design is an important aspect of providing information on the existence of specific infrastructure features that ADS can verify with its sensing capabilities. If roadway infrastructure information is stored as the baseline, updated or dynamic digital information transmitted either on a periodic or ad-hoc basis would enhance the ADS reliability. The digital infrastructure needs to be reliable enough, so that it serves as a supplement to avoid having all the sensors and computation power onboard the vehicles. Another aspect of digital information is that a little bit of information for all situations is more important than a lot of information for only a few situations. In other words, as long as there is one traffic light out there that doesn't follow any new initiatives, ADSs have to cater to traffic lights without digital features.

The industry believes that V2X will accelerate ADS' deployment in cities. For optimal performance of the ADS, a redundant path of Signals Phase and Timing (SPaT) signals from the traffic lights through V2X communication (DSRC, C-V2X, or cloud-to-cloud) would be helpful. Several respondents have recommended investing in this redundant SPaT signal layer for infrastructure where AVs will be operating. In this case, V2X is essential to provide traffic sign and traffic signal information.

## 2.6 Question 6

*How would you anticipate receiving such information? For example, through cellular connection onboard or dedicated communication units, such as DSRC[21] or dual cellular units (as proposed in Cellular V2X[22] concepts)?*

[21] Dedicated Short-Range Communication, https://www.its.dot.gov/communications/media/1probe.htm

[22] C-V2X, https://www.qualcomm.com/invention/5g/cellular-v2x

### Survey results

In the survey, 17 (85%) of the respondents answered this question. The results, including the preferred channels for receiving the digital infrastructure features, frequency, and reasons, are summarized in Table 11.

*Table 11. Anticipated channel(s) for receiving information of digital features of infrastructure and transportation operations*

| ***Channels*** | ***Frequency*** | ***Reasons*** |
|---|---|---|
| All channels work | 6 (35.3%) | "Receiving such traffic information in time through V2X is essential for ADS. No matter 5G or DSRC, ADS needs high speed and no latency data transmission." |
| Cellular | 4 (23.5%) | "The cellular connection is already on board in the vehicles.<br>Cellular technology is the anticipated delivery medium for the foreseeable future." |
| Dedicated channel | 4 (23.5%) | "We anticipate receiving such information through dedicated communications units, either DSRC or C-V2X. Both of these two are good as long as they are reliable and low-latency." |
| C-V2X | 3 (17.6%) | "Initially cellular but by mid-2020s C-V2X."<br>"Both DSRC and C-V2X are a contender at the moment, and the industry is still trying to figure out the benefits of one technology over the other. However, in general, it looks like C-V2X could win the race." |

- The most frequently (6, 35.3%) mentioned feedback is that all communication channels work as long as they are sent. More importantly, low latency is a critical criterion. As stated by one respondent, "All paths work for us: DSRC, C-V2X, and cloud-to-cloud. What's important is low latency (e.g., below 300-500 milliseconds)." Another consideration brought up by the respondents is the cost of either channel: "We are agnostic towards the communication protocol. We are, however, very cost-sensitive. So, the best solution is one that has multiple providers that are competing to drive the cost down and the quality up."
- There were 4 out of 17 (23.5%) respondents anticipated that cellular technology would be the delivery medium for the foreseeable future. One reason is that the cellular connection is already onboard in the vehicles. As stated by one respondent: "Important changes to infrastructure, such as planned construction and changes in signage, could even be communicated to ADS operators through emails. With regards to direct vehicle communication, a technology-neutral approach is recommended to ensure maximum flexibility for industry to develop." Another reason would be the lead-time needed for rule-making, technology development, and deployment for the dedicated communication if it will ever happen.
- Another 4 out of the 17 (23.5%) respondents anticipated receiving such information through the dedicated communication channel, either the DSRC or C-V2X.
- The rest 3 (17.6%) respondents anticipated that the C-V2X would win the race with DSRC. Therefore, initially, the communication channel would be the cellular connection. But it will transition to C-V2X in the timeframe of the mid-2020s.

### Interview results

Regarding preferred channels for V2X, as mentioned by several interviewees, “As long as the information is available, we can consume it in various ways.” Therefore, it was recommended that the industry reach an agreement on what V2X technology to use and then have a mass deployment and start accelerating AVs' deployment. When it comes to a safety-critical input to the ADS, it is very good to have more than one communication path. So a dedicated channel plus cellular connection would be good for safety-critical inputs.

## 2.7 Question 7

*How do you envision AV deployment in 3, 5, and 10 years?*

- *At what levels of automation, per SAE L1-L5?*
- *What do you believe will be the likely operational modes or targeted applications of higher levels of automation?*

As shown in Figure 7, the SAE J3016[23] standard defines six levels of driving automation, from SAE Level Zero (no automation) to SAE Level 5 (full vehicle autonomy). Below, we list the definitions for Level 3, Level 4, and Level 5 automation.

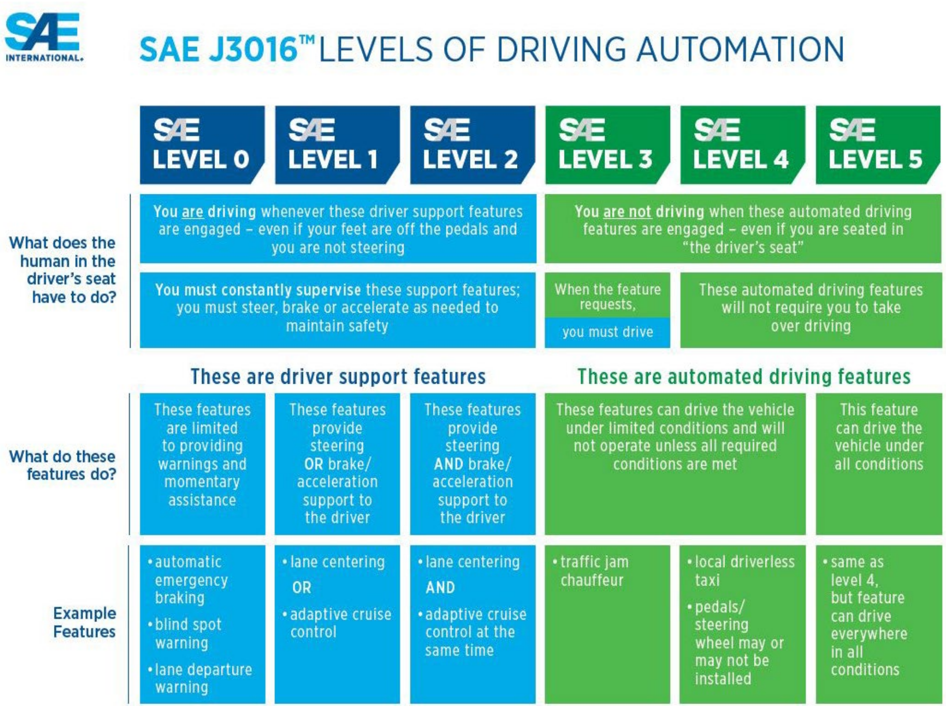



*Figure 7. SAE levels of automation (source: SAE website)*

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23 https://www.sae.org/standards/content/j3016_201806/

- **Level 3 (L3) Conditional Driving Automation:** The sustained and Operational Design Domain (ODD)-specific performance by an ADS of the entire Dynamic Driving Task (DDT) with the expectation that the DDT fallback-ready user is receptive to ADS-issued requests to intervene, as well as to DDT performance-relevant system failures in other vehicle systems, and will respond appropriately.
- **Level 4 (L4) High Driving Automation:** The sustained and ODD-specific performance by an ADS of the entire DDT and DDT fallback without any expectation that a user will respond to a request to intervene.
- **Level 5 (L5) Full Driving Automation:** The sustained and unconditional (i.e., not ODD-specific) performance by an ADS of the entire DDT and DDT fallback without any expectation that a user will respond to a request to intervene

### Survey results

In the survey, all 20 (100%) respondents answered this question. The results are shown in Table 12, including the timeframe, different levels of automation, frequency of the response, and deployment details.

*Table 12. AV deployment in 3, 5, and 10 years*

| ***Time*** | ***SAE Levels of Automation*** | ***Frequency*** | ***Anticipated deployment details*** | |
|---|---|---|---|---|
| In 3 years | L3 | 5 | Available on highways for mass-market; for consumers to purchase | “We expect L3 with humans in the loop AV to become popular in the coming 2 to 3 years. We are already seeing L2 features in production today, and in 3 years, L3 will be available in consumer vehicles.” |
| | L4 | 7 | Highway, geo-fenced in certain cities, constrained operation design domains;<br>Begin urban robo-taxi fleet scaling. | “L4 vehicles for mobility services are running real-world trials now. In 3 years, the launch and scaling of L4 vehicles will begin, primarily with mobility-as-a-service (MaaS) fleets of L4 AVs for ride-hailing, ride pooling, and first/last mile or bus/shuttle routes.” |
| In 5 years | L3 | 2 | Large scale L3 passenger cars; | “L3 in a large number of models (on controlled-access highways).” |
| | | | L3 trucks | “L3 transportation trucks drive across the country and freeways.” |
| | L4 | 8 | Large scale in cities | “L4 for a larger-scale deployment in cities.” |
| | | | Evolving towards L4 on special routes as ownership | “L4 vehicles for consumers to purchase become broadly available, especially in the premium vehicle segment.” |
| | | | Public transportation (shuttles) or urban environment as service | “Urban Pilot as public transportation (shuttles, on dedicated lanes, such as taxi and bus lanes).” |
| | | | Small scale deployment;<br>In geo-fenced area | “With small scale (geo-fenced areas), within 3-5 years for early deployment.” |
| | | | L4 operation of trucks | “Have commercial L4 trucks operations in jurisdictions that allow within 3-5 years.” |
| In 10 years | L3 | 2 | None controlled-access highways | “L3 extended to none controlled-access highways.” |

| | | | | |
|---|---|---|---|---|
| | L4 | 7 | L4 fleet and also available for consumer purchase | "L4 MaaS fleets, as well as consumer vehicles, will be more broadly available and deployed." |
| | | | L4 in urban environment with good infrastructure or with geo-fenced area | "L4 in urban-environment with city speeds, within geo-fenced areas." |
| | | | L4 within specific ODD available for consumer purchase | "L4 systems within very specific operational domains could become available in high-end vehicles within 10 years and lead to a competition to cover more and more operational domains every year." |
| | | | L4 in shuttles and for goods delivery | "L4 or higher will be used for shuttles in restricted or private areas for limited people." |
| | L5 | 1 | Robo-taxi and public transportation | "L5 on both highway and urban: Robo-taxi and public transportation." |

A 3-year timeframe is relatively near, from the perspective of vehicle fleet deployment or production. It seems that most respondents have clear pictures of the AV deployment, especially for SAE L3 and L4 automation.

- As commented on by 5 (25%) respondents, L3 automation (highway pilot) would be available for consumers to purchase. It mainly works in the highway traffic environment.
- According to 7(35%) respondents, L4 automation, primarily as mobility service fleets, will begin to scale up. However, the L4 automation is limited to constrained operation design domains (ODDs) on highways and certain cities.

Respondents' predictions about AV deployment in 5 years are less consistent than their predictions for the 3-year timeframe.

- Two respondents commented on the L3 automation in 5 years. For passenger vehicles, L3 automation running on controlled-access highways would be available on a large number of vehicle models for the mass market. L3 trucks will be available across the country on controlled-access highways.
- For L4 automation, 8 (40%) respondents commented. However, the detailed deployment modes and scale are quite different. The boldest predictions are that L4 automation will have large-scale deployment in the urban driving environment, and it will become broadly available for consumer purchase in the premium vehicle segment. The rest of the predictions are less optimistic. For passenger vehicles, the L4 automation is likely available as public transportation or mobility service or in early deployment within ego-fenced areas. For trucks, L4 automation could be commercially available in certain jurisdictions.

Respondents' predictions for AV deployment in 10 years are similar to their predictions of AV deployment in 5 years. In total, 10 (50%) respondents provided their feedback.

- Two respondents envisioned that within 10 years, L3 would extend to none controlled-access highways.
- Seven respondents commented on L4 automation. The boldest prediction is that the L4 mobility service will be broadly deployed, and L4 vehicles will be available for consumers to purchase. Some

other relatively conservative predictions are: L4 will be deployed in urban environments within geo-fenced areas or with very good infrastructure conditions; and L4 running on specific ODD will be available for purchasing. The most conservative prediction for L4 in 10 years is that it will only be used for shuttles in restricted or private areas.

- Only one respondent commented on L5 automation in 10 years. The prediction is that the L5 will be available on both highway and urban as robo-taxi and public transportation.

### Interview results

During the interview, respondents were further asked about their perspectives of a detailed timeline for different levels of automation.

- To better understand this question, it is helpful to re-think what is considered deployment. It could be that high automation is only released in constrained domains of certain countries/markets or broadly available everywhere in every market. One reason is the particular challenges other than the technology itself confronted in different markets. One aspect of the challenges is legal liability. The legal liability of car manufacturers in the US is much more challenging than in Europe and other regions. For higher automation levels (L3 and above), where the vehicle is driving itself until the human driver takes over, the car manufacturer is responsible for whatever happens while the car is in automation mode. Another challenge is the cost of the ADS. Many car manufacturers are working on bringing down the cost and making the system as cost-effective as possible.
- Another important notion is the operational domain. A freeway driving environment, although high speed, but is an uncomplicated traffic pattern. However, with different road users in the urban driving situation, it is rather more complicated than the freeway driving environment. Nevertheless, already some L4 automated shuttle is deployed, for example, in Florida's retirement community at a lower speed (e.g., less than 25 miles per hour). Thus, the operational domain matters when talking about AV deployment.
- Several respondents also commented on the AV deployment beyond 10 years' timeframe. The emergency of L2+ ADS features points towards the potential for higher-level automation year over year. The general availability of L4 and/or L5 (high and full automation) across vehicle segments will take decades.
- Only one respondent commented on the L5 automation. Some other respondents mentioned that their company would solely focus on the even automation levels (L2 and L4). In other words, they are skeptical about the SAE L5 vehicles being ready to run in every circumstance everywhere.

Overall, the respondents share the notion that AV development is an incremental process. The AV industry is in a state of growth as well as flux. Most of the respondents believe in the mode of shared mobility for people transportation and good movements in predefined environments. That way, the fleet and service providers will continue to own the vehicles. Regarding ownership of L4 or L5, it will be driven by the acceptance of the L4 or L5 mobility service.

## 2.8 Question 8

*What types of infrastructure policies do you believe state and local agencies should consider related to the deployment cases identified in the previous question?*

- *Do you see evolving changes in the needs of infrastructure support, as deployment progresses? If so, in what ways?*

## Survey results

Eighteen (90%) respondents answered this question. Table 13 summarizes the most-mentioned infrastructure policies that state and local agencies should consider.

- The respondents most frequently mentioned V2X policy. The 7 respondents shared the expectation that the state should consider the V2X policies, such as equipping the traffic signals and providing V2X information. With the V2X, many onboard perception and localization tasks can be facilitated, which will improve the safety and reliability of the technology.
- Physical infrastructure maintenance was the second most frequently mentioned policy by 4 respondents. Firstly, they expect policy support for better maintenance of the infrastructure's physical elements, such as lane markings and road signage. Secondly, they expect policy support for the maintenance of specific operational routes. Policy support for adaptation of specific locations and compliance with autonomous vehicle technologies (e.g., some intersection scenarios mentioned in Question 1) are suggested.
- Three respondents mentioned the policy for digital infrastructure. For local agencies, they expected cities to provide up-to-date digital maps. They expect a standard map that would define the automation level availability for considered zones within the state.
- Three respondents expected both state and federal policies for dedicated AV lanes on interstate highways, which could foster platooning and increasingly functional operational domains.
- For testing and licensing, two respondents expected the state to support L4 testing of commercial fleet trucks over 10,000 pounds.
- Three respondents mentioned other policies for dedicated pick-up and drop-off locations and charging stations. Such policies would be useful for L4 and L5 deployments if there are dedicated drop-off zones to facilitate AVs' loading and unloading. Infrastructure for curbside pick-up and drop-off for passengers should be ADA complied. As many AV companies focus on deploying electric autonomous vehicles, the availability of charging facilities is important.

*Table 13. Infrastructure policies*

| **Policies** | **Frequency** | **Details** |
|---|---|---|
| V2X | 7 | A lot of onboard perception and localization tasks can be facilitated by V2X and smart infrastructure, which in turn will improve safety and reliability.<br>For example, to process all algorithms such as lane marking detection, traffic light detection, and so on, the ADS needs very high-cost computation, which will slow down ADS deployment. Digital infrastructure such as V2X can help this.<br>Policies making high speed, secure wireless data communication at an affordable cost will be crucial.<br>The state should consider digital infrastructure policies, such as equip the traffic signals and provide V2X information such as traffic signal phase. |
| Physical infrastructure maintenance | 4 | Policy for better maintenance of the infrastructure's physical elements (lane markings, road signs) will play an important role in AV deployments. |

| | | |
|---|---|---|
| | | Expect the maintenance of specific operational routes. Adaptation of particular locations to make them compliant to autonomous vehicle technologies (e.g., some intersection scenarios). |
| Up-to-date digital map | 3 | Expect cities to provide up-to-date digital maps.<br>Expect the state to define a standard map that would define the automation level availability depending on considered zones. |
| Dedicated AV lanes | 3 | State and federal infrastructure policies for dedicated AV lanes on interstate highways could foster platooning and increasingly functional operational domains. |
| Testing and licensing | 2 | The state should support the L4 testing of commercial heavy trucks. California is missing all the learning opportunities and deployments due to the lack of regulations. |
| Others (e.g., dedicated pick-up and drop-off locations; electric vehicle charging stations) | 3 | It would be useful for L4 and L5 deployments if there are dedicated drop-off zones to facilitate the loading and unloading of AVs.<br>Infrastructure for curbside pick-up and drop-off for passengers should be ADA complied. The point for accessibility is that the infrastructure should be available and be well maintained.<br>Many AV companies are focusing on the deployment of electric autonomous vehicles. The availability of charging facilities is important. |

### Interview results

During the interview, respondents provided more open-minded feedback for infrastructure policies.

V2X could be used as a data source for self-driving. A lot of self-driving companies think it'll be great when it's well defined and implemented, but for right now, it's too uncertain to count on it. They suggested that V2X is something that California DOT or DOTs across the US and other countries should focus on. C-V2X or DSRC can provide data to inform vehicles better about road conditions and traffic conditions will be essential in the future.

For maintenance of physical infrastructures, several respondents suggested that a more proactive approach of maintenance should be taken: "As state and local agencies evaluate how best to anticipate shifting needs of ADS technologies from an infrastructure investment perspective, it may be necessary to shift from a repair-as-needed approach to a preventative-maintenance approach. There are many public rights-of-way in the state that are not up to date in terms of standards. However, these streets and roads are not being proactively brought up-to-code until major resurfacing or other work is done. Ensuring a more consistent and proactive approach will help optimally prepare the existing infrastructure for ADS technologies.

Policy for dedicated lanes on interstate highways was expected from the federal level. However, there are different voices. Instead of dedicated lanes, some respondents suggested defined zones with certain areas, where robo-taxi service is likely to be deployed first. Within the defined zones, the issues mentioned in Question 4, such as the intersections and the signage, can be targeted to make sure the lanes are properly marked, and roads are maintained. If the state tries to do everything, it will not have nearly enough resources, and it's not going to be done nearly with any consistency. Therefore, dedicated lanes are not necessarily the choice, but defined zones would be a better approach. Besides, another respondent also expected the passage of SAE level 4/5 regulation and legislation (by 2021) that will allow homologation, certification, and launch of MaaS services with self-driving vehicle fleets. Another respondent expressed the support of the wide harmonization of policies within the nation.

Regarding regulations for AV testing, two respondents expected the state to support L4 testing of commercial fleet trucks over 10,000 pounds. As commented, many companies who have truck divisions have moved out of California, most now in Texas. California is missing the learning opportunities and potential deployments due to the lack of regulations, while other states will take advantage of that. The respondents expressed the concerns that this policy will probably have much impact on the L4 truck deployment in the next 3-5 years in California.

Two respondents complained about the lack of a clear set of rules from one authority for AV testing. In Europe, there's a very consistent set of rules that everybody knows. If there are exceptions to that, it can be dealt with on a case-by-case basis. But in the US, there is no comprehensive set of rules. Every jurisdiction tries to impose its own rules and doesn't really care what other jurisdictions do. Therefore, it would be important for DOTs to implement uniform policies and procedures that support ADS operating across multiple jurisdictions. Besides, it is also important for the state to develop a consistent approach for effectively engaging OEMs for the AV testing or deployment.

Overall, from both the survey and the interviews, respondents share the understanding that “We expect the infrastructure to be rolled out in phases with improvements over time, while technology will work with what's available.”

## 2.9 Question 9

*What are the venues or mechanisms for governmental agencies to interact with the industry? Are there commonly accepted industrial standards and/or best-practice guidelines related to infrastructure that you might recommend?*

### Survey results

In the survey, 17 (85%) of the respondents answered this question.

Regarding venues for governmental agencies to interact with the AV industry,

- The most mentioned venues are AVS, TRB, NHTSA, and FHWA conferences or meetings on Automated Vehicles;
- Society of Automotive Engineers (SAE) automated vehicle committees meetings or events;
- Consortiums with government and industry representatives. For example, the Automated Vehicle Safety Consortium[24].
- Besides, respondents also mentioned California DMV’s efforts for regulating the research, development, and operation of autonomous vehicles as an important venue.
- Other mentioned venues include published White Papers (such as the Safety First for Automated Driving[25]), as well as individual dialogs with authorities.

[24] https://avsc.sae-itc.org/

[25] https://www.daimler.com/documents/innovation/other/safety-first-for-automated-driving.pdf

Regarding commonly accepted industry standards and/or best-practice guidelines related to infrastructure,

- Manual on Uniform Traffic Control Devices (MUTCD) is mentioned as one of the standards of infrastructure;
- FCC and NHTSA are recommended for industrial standards;
- Standards organizations like the SAE and ISO remain the best places to obtain feedback from a broad spectrum of industry players;
- Another mentioned source of best practice is guidelines issued after pilots in partnership with governmental agencies.

### Interview results

Many respondents agree that having a venue for engagement between the governmental agencies and the AV industry, and having standards or best-practice guidelines related to infrastructure are very important for AV research and development. The use of consortiums to improve industry engagement is encouraged. There should be more government and industry collaborations happening where safety is concerned (e.g., sharing data).

## 2.10 Question 10

*What data might your company be willing to share that would be beneficial for public agencies? Have any open data sets been developed by the AV industry that would be similarly beneficial? For example, data regarding vehicle operating conditions (speed, route traveled, occupancy, etc.), operating environment (traffic conditions, congestion, incidents, etc.), or observed infrastructure damage (downed signs, pot holes, malfunctioning signals, etc.).*

### Survey results

In the survey, 14 (70%) respondents answered this question. As shown in Table 14,

- Out of the 14 respondents, 10 (71.4%) respondents were willing to share data with the public agencies. Some of these companies are completely open to data sharing "We are open to sharing any data we have." Some others mentioned that "For the purpose of AV testing in California, data can be shared with respective agencies, as we are currently required to file the annual disengagement reports filed to the California DMV."
- The other 4 (28.6%) of the respondents were not willing to share data. Some of these respondents further explained that they had concerns about revealing their proprietary information "As we are an advanced AV development engineering group, the data sets we do collect probably aren't suitable for sharing outside of the company at this time due to the confidential nature of the types of data we collect." Some respondents have limited resources (e.g., labor) for data sharing as "it is hard for us to provide data sets with that information because we have a very limited budget and labor power as a start-up."

*Table 14. Willingness for data sharing*

| ***Willing to share data*** | ***Frequency*** | ***Reasons*** |
|---|---|---|

| | | |
|---|---|---|
| Yes | 10 (71.4%) | "We are willing to share any data that might help infrastructure, including poor road conditions, traffic rule violations, traffic conditions, and broken road facilities."<br>"We have collected lots of actual driving data on real roads and would appreciate collaborations with public agencies, such as sharing them and/or analyzing them together." |
| No | 4 (28.6%) | At this moment, we don't want to share any specific data with any public agencies. |
| Total responses | 14 (100%) | |

Some respondents who were positive for data sharing with public agencies further suggested approaches for interactive engagement with AV industry companies for data sharing and maintaining the infrastructure, which would benefit AV deployment. For example,

- The public agencies can interact with the industry by sponsoring workshops or through 3rd parties like PATH. The company will be willing to share any data that can be used as evidence to support the claim of needing additional physical or digital infrastructure or any data that would be useful to increase the level of safety for AVs.
- It would be useful for the AV industry to report road damage, poor lane markings, or other obstructions to public agencies for timely rectification. The agreement will be required to prioritize each observation's severity to make the data more meaningful.
- It would be more helpful if there could be some funding behind these efforts of data sharing and data analytics to justify a joint effort.

Many open data sets have been developed by the AV industry. Those ones include road user detection, instance segmentation, drivable area, camera, and LIDAR data (Waymo, Kitti, etc.). However, the available datasets do not provide context to situations such as infrastructure damage or deteriorated road markings.

## Interview results

Some interviewees shared their further thoughts about data sharing. Data sharing is complicated. Overall, there is a need for agreement on or standardization of what format and what level of information is required.

- Firstly, there would need some agreement on or standardization of what constitutes a poor roadway;
- Secondly, AV testing could generate a huge amount of data, for example, one terabyte of information every hour of driving. In contrast, a very small fraction of that data would be related to the assessment of road conditions. Here arise two questions: how to transfer the information and how to aggregate it.
- Thirdly, the data AV companies collect are not stored in a representation that reduces to specific ADS roadway measurable. The collection is focused principally on capturing characteristics specific to ADS vehicle operation and not the roadways in general.
- Last but not least, what human validation or verification of the shared information would be needed? If humans in the loop are needed, which is likely the case, before or after sharing the information, it will require resources.

There are concerns about revealing proprietary information. One respondent mentioned that the company is comfortable with sharing data. However, their business partners, like the shipping partners and fleet partners, would see their data and how they move their goods around this country as Intellectual Property.

Overall, from the AV companies' perspective, the AV testing data is mainly focused on the performance of automated driving systems, but not the roadway features or measurements. There are also various concerns regarding proprietary information embedded in the data, potential liability issues, or the amount of labor work needed for annotating the data before sharing. These are all reasonable concerns from the industry. Regardless, as the first step of this mutually beneficial effort to both the AV industry and IOOs, it is highly recommended to initiate direct and in-depth conversations between the state agencies and critical industrial stakeholders. It is also recommended to begin the research effort for tools and algorithms that would facilitate data sharing and data processing for this purpose.

## 2.11 Open comments

*We welcome any open comments on infrastructure needs in addition to the questions above.*

In the survey, only 4 (20%) respondents provided feedback. Among the four responses, one is trying to simplify the infrastructure need for AV by stating that "In general, what is good for a human-driven vehicle is good for an AV. What can be easily seen by a human driver can be seen by our camera system." One response is about the HD map standard "A truly open and widely accepted map format is missing." Another response emphasizes the importance of infrastructure for AV deployment and expects "to see an annual conference devoted to federal and state infrastructure and safety policies." The last response concerns the financial needs for building up and maintaining the infrastructure "heavy investment is needed for building up the infrastructure. However, where is the money from?"

## 2.12 Summary

Based on respondents' feedback in the online survey and the follow-up interview, we found that

- The most important roadway characteristics that will benefit the ADS are (1) digital map and signage; (2) lane markings; (3) work zone and incident information; (4) V2X; (5) traffic signals; (6) general signage; and (7) lighting.
- Respondents provided information related to quantifiable specifications for HD map, V2X data frequency, and lighting. Other than that, not much information regarding standards or specifications for the roadway characteristics is available yet.
- Most respondents agreed that the infrastructure would need to be monitored and maintained more stringently if state DOTs want to promote ADS capability on the roadways. AV companies are interested to know or obtain information regarding when road segments are non-compliant with the standards.
- The most frequently mentioned physical infrastructure issues are associated with lane markings, signage, traffic signals, and others such as work zones, flashing lights, and retroreflectors.
- Work zone and road closure, traffic signal phase and timing, traffic congestion or real-time traffic information, general V2X, and HD maps were most highly expected digital infrastructures to help accelerate ADS deployment
- Regarding preferred channels for V2X, the majority respondents thought as long as the information is available, they can consume it in various ways. Therefore, it was recommended that the industry

should reach an agreement on what V2X technology to use. When it comes to a safety-critical input to the ADS, it is very good to have more than one communication path. So a dedicated channel plus a cellular connection would be good for safety-critical inputs.

- All respondents share the notion that AV development is an incremental process. Most of the respondents believe in the mode of shared mobility for people transportation and good movements in predefined environments. That way, the fleet and service providers will continue to own the vehicles. Regarding ownership of L4 or L5, it will be driven by the acceptance of the L4 or L5 mobility service.
- Most respondents shared the expectation that the state should consider the V2X policy, such as equipping the traffic signals and providing V2X information. They expected policy support for better maintenance of the infrastructure's physical elements, such as lane markings and road signage, as well as for the maintenance of specific operational routes.
- Most respondents agree that having a venue for engagement between the governmental agencies and the AV industry, and having standards or best-practice guidelines related to infrastructure are very important for AV research and development. The use of consortiums to improve industry engagement is encouraged. There should be more government and industry collaborations happening where safety is concerned (e.g., sharing data).
- Regarding data sharing, from the AV companies' perspective, the AV testing data is mainly focused on the performance of automated driving systems, but not the roadway features or measurements. There are also various concerns regarding proprietary information embedded in the data, potential liability issues, or the amount of resources needed for annotating the data before sharing. These are all reasonable concerns from the industry. Nevertheless, as the first step of this mutually beneficial effort to both the AV industry and IOOs, it is highly recommended to initiate direct and in-depth conversations between the state agencies and critical industrial stakeholders. It is also recommended to begin the research effort for tools and algorithms that would facilitate data sharing and data processing for this purpose.

# Appendix A: Questionnaire Cover Page

***Why do we need a questionnaire/survey?***

AV deployment has the potential to bring about transformational changes to the transportation sector and society as a whole. State and local agencies who own, maintain, and operate the infrastructure have the opportunity to work jointly with the AV industry to provide for safe and efficient operations. A key question being asked by the agencies is: "What transportation infrastructure improvements or modifications do AV manufacturers believe will facilitate and improve AV performance?" This questionnaire/survey is designed to address this question.

***Who will receive the questionnaire/survey?***

Those who have obtained an AV testing permit from the California Department of Motor Vehicles (DMV) will be contacted. The project team will also reach out to other stakeholders who are involved in the AV industry, even though they may not hold a DMV testing permit or conduct tests directly.

***What level of automation is covered by this questionnaire/survey?***

All levels of Automated Driving Systems (ADS, as defined in SAE J3016[26]) are included in this survey including driver assistance (such as L1 lane keeping), partially automated (such as L2 lane keeping plus adaptive cruise control), and dynamic driving tasks (such as L3, L4 and L5 operations).

***Who is sponsoring the study?***

The California Department of Transportation (Caltrans[27]) is sponsoring this study. Caltrans is the owner and operator of 51,000 plus miles of highways in California. Caltrans mission calls for a safe, sustainable, integrated and efficient transportation system to enhance California's economy and livability.

***How will the results of the study be used?***

Caltrans and other State and local agencies in charge of operation and maintenance of the infrastructure may use the information derived from this study to inform their planning, design, construction, and maintenance plans for transportation infrastructure.

***Who is conducting the study?***

California PATH[28] at the University of California Berkeley is a pioneering research organization that has been dedicated to vehicle automation and transportation research since 1986. A research team from California PATH will conduct the survey and follow-up interviews, collect responses, and consolidate the inputs into a summary report.

***What kinds of questions will be asked?***

[26] SAE J3016, https://www.sae.org/news/2019/01/sae-updates-j3016-automated-driving-graphic
[27] Caltrans, https://dot.ca.gov/
[28] California PATH, https://path.berkeley.edu/

A list of the questions is provided in the following pages.   Many of the questions ask the respondents to identify roadway characteristics, enhancements or modifications that may help to facilitate safe and efficient operation of AVs on California roadways.  Roadway characteristics may include physical things such as lane markings, signage, highway lighting, guardrails, crash barriers, traffic control devices, interconnection with highway-rail at-grade crossings, and other physical features of the roadway. They could also include digital features such as provision of real time map updates, digital signage, signal phase and timing, incidents, work zone information, roadway closure, and construction zone information.

Most of the questions are open-ended. We welcome comments and suggestions on additional information that will enhance the outcome of this study.

***Your response will stay anonymous and your privacy will be protected***

California PATH has many years of experience in carrying out similar studies.  The protocol of the survey will be reviewed and governed by the Internal Research Board[29] of UC Berkeley.  The responses will remain anonymous.  No confidential or proprietary data will be revealed, although we do not intend to collect information of such nature.

***What are the next steps following the questionnaire/survey?***

If the respondent is receptive to further discussions, a phone call or in-person interview may be scheduled.  All inputs from the questionnaire and interviews will be categorized and consolidated into a summary report.  The report will also be distributed and shared with the respondents and made publicly available at the end of this project. It should be noted that not all recommendations or suggestions from the survey will or can be fully implemented.

***Guidance to completing the questionnaire/survey***

There is a total of 10 questions in the questionnaire.  In each question, there may be multiple levels of information that are relevant to the question.  To lessen the burden on respondents, the questions are relatively high-level, and provide total flexibility in how you may respond.  Feel free to expand and offer detailed answers.

You may provide your answers on the electronic PDF file and send back by email to [email]. Alternatively, you may provide your responses on a web-based Google form available via this weblink: https://forms.gle/uGF58cqVChc4hLLF8 .

If you need further explanation or clarification regarding the survey questions or process, please email Peggy Wang (peggywang@berkeley.edu) and Ching-Yao Chan (cychan@berkeley.edu) or call us at 510-665-3621.  If you are willing to participate in a follow up meeting, please provide your contact information at the end of the questionnaire.

[29] Human Research Protection Program, UC Berkeley, https://cphs.berkeley.edu/

## Appendix B: Survey Questions

(1) What roadway characteristics or features do you believe will benefit your ADS systems? You can choose to prioritize them into high, medium and low factors. Examples of roadway features include lane markings, signage, lighting, traffic signals, digital maps and signage, work zone and incidents information, V2X data, etc.

(2) Are there any specifications or standards associated with the roadway characteristics that you believe would support a minimum performance level? If possible, please provide quantifiable specifications or use specific terms. Some exemplar types of specifications include level of contrast for lane markings, lighting, visibility, markings for barriers, etc.

(3) Deterioration is common in infrastructure, and maintenance is performed periodically. Do you see the need for different infrastructure maintenance requirements when considering the use of ADS rather than human-driven vehicles? How might the degradation of roadway features affect your system?

(4) What particular issues (if any) exist for ADS to interpret certain physical infrastructure elements, such as lane marking, traffic signals, HOV/bike lanes, and signs? Please give specific examples if applicable.

(5) What types of digital features of infrastructure and transportation operations, if available, do you believe would help accelerate safe and efficient deployment of the ADS? Types of information include traffic signal phase and timing, work zone or road closures, incidents, traffic congestion, etc.

(6) How would you anticipate receiving such information? For example, through cellular connection onboard or dedicated communication units, such as DSRC[30] or dual cellular units (as proposed in Cellular V2X[31] concepts)?

(7) How do you envision AV deployment in 3, 5, and 10 years?
- At what levels of automation, per SAE L1-L5?
- What do you believe will be the likely operational modes or targeted applications of higher levels of automation?

(8) What types of infrastructure policies do you believe state and local agencies should consider related to the deployment cases identified in the previous question?
- Do you see evolving changes in the needs of infrastructure support, as deployment progresses? If so, in what ways?

[30] Dedicated Short-Range Communication, https://www.its.dot.gov/communications/media/1probe.htm
[31] C-V2X, https://www.qualcomm.com/invention/5g/cellular-v2x

(9) What are the venues or mechanisms for governmental agencies to interact with the industry? Are there commonly accepted industrial standards and/or best-practice guidelines related to infrastructure that you might recommend?

(10) What data might your company be willing to share that would be beneficial for public agencies? Have any open data sets been developed by the AV industry that would be similarly beneficial? For example, data regarding vehicle operating conditions (speed, route traveled, occupancy, etc.), operating environment (traffic conditions, congestion, incidents, etc.), or observed infrastructure damage (downed signs, pot holes, malfunctioning signals, etc.).

We welcome any open comments on infrastructure needs in addition to the questions above.

We would like to follow up with an interview after this questionnaire, to better understand and discuss your comments and suggestions. The interview protocols will follow the same privacy protection required by the IRB process. If you are open to such interactions, either by phone or by video conference, please let us know how we may contact you.


## Acknowledgment

The survey responses and interview feedback were collected between May and September, 2020. The PATH team appreciate all the respondents, for taking their time responding to the survey and the interview, and sharing their valuable inputs.